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TECHNICAL REPORT 1777
January 1999

Sediment Quality Characterization Naval Station San Diego: Final Summary Report

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The work detailed in this report was performed for Navy Region Southwest Environmental Department by the Marine Environmental Quality Branch, Code D362, SSC San Diego.

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EXECUTIVE SUMMARY

This report summarizes a study that was carried out to characterize the current status of San Diego Bay sediment quality in the vicinity of Naval Station San Diego (NAVSTA). The objective of this study was to provide an assessment of the extent and potential ecological consequences of sediment contamination. The study focused on two issues: the characterization of contaminated sediments, and the evaluation of processes that control the levels, transport, and biological exposure of this contamination. The scope of the study was limited to evaluation of sediment quality, and processes acting on those sediments, for the region offshore from NAVSTA. The term "NAVSTA region" is used throughout this report to represent the study area extending approximately from the Sweetwater River on the south, to the Coronado Bridge on the north, and from the NAVSTA shoreline on the east to the Silver Strand on the west. The term "NAVSTA pier area" is used to refer to the are extending from Pier 1 to Pier 13 out to the NAVSTA pierhead property line. Sediments were characterized on the basis of a range of physical, chemical, and toxicological testing. Processes that were evaluated included contaminant sources, sediment transport, sediment-water exchange, and degradation. As part of the study, new technologies for assessment and remediation were demonstrated alongside traditional methods.

On the basis of comparison to Effects Range Median (ERM) levels and background contamination levels in relatively "clean" regions of the California coast, this study describes which particular contaminants appear to be elevated and in what spatial areas elevated levels were found. In general, concentrations of copper, mercury, and zinc were measured at elevated levels, concentrations of silver, lead, PAHs, and PCBs were occasionally found at elevated levels, and concentrations of arsenic, chromium, and nickel were mostly found to lie below ERM thresholds and at or near background levels. Contaminants often tended to co-occur (e.g., copper and zinc), and were often associated with regions of high fines content (i.e., clay and silt). Spatially, contaminant levels exceeded ERM thresholds in the region along the quay wall between Piers 2-5. Within this region, silver, copper, mercury, zinc, and PCBs were found at levels exceeding the ERM. Moderate incidence of elevated contaminant levels were observed in regions along the quay wall between Piers 5 through 7 (copper, mer-cury, lead, zinc, and PCBs), the region along the outer portion of Piers 2 through 5 (copper, mercury, zinc and PCBs), and the region within the entrance to Paleta Creek (mercury, zinc, and PCBs). The remaining areas within the piers had a relatively low incidence of elevated contaminant levels.

Biological effects from sediment exposure were evaluated on the basis of a number of studies encompassing a broad range of test organisms and exposure mechanisms. Tests included bioassays, benthic community structure, in-situ biomarker assays, and bioaccumulation studies. Specific relationships between the physical and chemical characteristics of the sediment and biological effects were difficult to discern. Sediments from many sites were found to be degraded to some extent, however, the spatial distribution of biological effects did not show clear patterns in relation to contaminant and physical property distributions. Regions with low incidence of chemical contamination displayed a broad range of biological effects, while regions with high incidence of chemical contamination generally showed a high incidence of toxicity. Areas in which high incidence of contamination and biological effects co-occurred were confined to the region along the quay wall between Piers 2 and 7.

Sediment elutriate toxicity was examined to determine if exposure that occurs during resuspension events could lead to effects in Bay organisms. This type of exposure could occur as the result of ship movements. Laboratory elutriate exposures were compared to expected exposure levels in the field. The results indicate that acute toxicity due to exposure during resuspension events is unlikely.

Results from previous studies of benthic community health were supplemented using Sediment Profile Imaging (SPI) technology. The SPI system allows for rapid characterization of physical and biological indices of sediment quality through the acquisition and analysis of vertical-profile photographic images. Results from 43 sites revealed that the sediment quality and benthic habitat in the NAVSTA region of San Diego Bay were within what would be considered the normal range, given the water depth, amount of vessel traffic, and range of activities associated with operation of a naval station. Compared with SPI surveys done in other urban harbor areas in similar water depths, the majority of images from the vicinity of NAVSTA indicated relatively high habitat quality and showed little evidence of adverse impact or potential contaminant "hot-spots," as reflected in benthic community structure and sediment texture. Only five of the locations analyzed showed any signs of serious adverse impacts.

Biomarker analysis of water column and infaunal mussels showed a strong relationship with sediment contaminant levels. The highest effect levels were found along Pier 4 where results suggest metals as the likely cause. Bioaccumulation results using mussels indicate that metals and hydrocarbons were available to filter feeding organisms at NAVSTA locations at higher concentrations than at the reference sites. The stations most highly affected were those closest to the quay wall where dispersal and dilution of contaminated fine sediments was lowest. Mussel tissue concentrations were elevated in copper at several stations compared to published seafood consumption thresholds. Mussel tissue concentrations of zinc correlated strongly with water levels.

Current estimates indicate ongoing sources of contaminants of concern including copper, zinc, lead, and PAHs in the NAVSTA region. For other chemicals of concern, some sources were identified, but either could not be quantified, or appear too small to be significant. Loading estimates were made for the NAVSTA region only and do not reflect overall sources to the San Diego Bay. Ship hulls appear to contribute much of the copper input to the region, with the remainder coming from stormwater runoff and pleasure boat hulls. Input of copper from antifouling paints will probably continue for at least several years until alternatives are developed. The majority of the copper in stormwater comes from sources upstream of NAVSTA, with Chollas Creek as the largest single source. A large portion of the ongoing zinc input to the region comes from zinc anodes on ships, with a slightly smaller percentage coming from stormwater runoff, and the remainder coming from antifouling paints and anodes on pleasure boats. Some input of zinc from anodes will probably continue indefinitely although loadings may be reduced significantly by increased use of "impressed current" cathodic protection systems. The majority of zinc in stormwater comes from sources upstream of NAVSTA, with Chollas Creek as the largest single source. Ongoing lead input comes primarily from stormwater, with the exception of a small contribution from atmospheric deposition. Until recently, the majority of the PAH input came from creosote pier pilings while the remainder came from stormwater runoff, oil spills, compensating fuel-ballast systems, atmospheric deposition, and bilgewater discharges. Inputs from bilgewater have recently been eliminated and ~50 percent of the pier pilings at NAVSTA have been replaced

with plastic or untreated wood. Currently, the loading to the region has been reduced by almost half, and total elimination of the creosote pier pilings along with bilgewater discharges will greatly reduce the remaining inputs to the region. Low-level inputs of mercury, silver, and cadmium have been identified in stormwater; however, known sources do not appear to account for measured levels in sediments. Sources of these contaminants may be historical. PCBs have been measured in stormwater at low levels; however, at present there is insufficient data to quantify overall source inputs to the region. Historically, PCBs have been associated with both industrial discharges and municipal waste discharges.

Three mechanisms for remobilization and transport were investigated in this study including benthic fluxes, leaching from sediments resuspended by ships, and tidal transport of sediments resuspended by ships. Tidal transport of sediments introduced with storm-water was also evaluated. These mechanisms serve to re-introduce chemicals from the sediment to the water where they are potentially more bioavailable. They also serve to redistribute chemicals and particulates to other regions of the bay and potentially to assist in removal to the ocean. Benthic flux measurements indicate that sediment release was most common for zinc with highest fluxes at Pier 4 and Paleta Creek. Release rates for copper, lead and cadmium were generally quite low. High PAH release was observed at Pier 8 where high bulk levels and pore water concentrations were also found, while little release was observed at Paleta Creek and the reference site.

A survey of ship movements at NAVSTA indicates fewer than five per day with 1 to 2 tugs per ship for a total of about 1730 ship movements per year. Field measurements indicate an overall sediment resuspension representing about 29 percent of the background suspended load as a whole, and about twice the estimated loading from episodic stormwater inflow to the region. Some desorption was observed for all metals during laboratory resuspension experiments but especially for zinc. Estimated remobilization for zinc was similar to the input from benthic fluxes. Input of cadmium from resuspension, although much less than zinc, is significant compared to other known sources. Although not necessarily indicative of environmental degradation, these values suggest that remobilization is an important mechanism for zinc and cadmium; all other contaminant inputs from remobilization were comparatively insignificant. Numerical transport modeling of sediments resuspended by ships carried out for events within the NAVSTA pier area indicates that about half of the resuspended material is deposited outside the pier area. Results also suggest that a rough balance exists between sediments deposited in the pier area by storm events and sediments removed from the pier area by ship resuspension events. Simulations of sediment-sorbed PAHs and metals indicate that about 60 to 70 percent of the contaminants resuspended during these events would be exported from the pier region.

Modeling of sediment inputs from stormwater showed that the spatial transport and fate of fine particles (less than 12 μm) and associated contaminants (e.g., copper) extends throughout the bay. Deposition of medium size particles was confined to areas within 1 to 2 km of the creek outfalls, and the coarse particles settled out right at the outfalls. Since the outfall of Chollas Creek is adjacent, and that of Paleta Creek is within NAVSTA, a large fraction of storm event TSS and copper loading gets deposited on the bottom sediments of NAVSTA. It is estimated that about 13 to 35 percent of the total loading from Chollas Creek, Paleta Creek, and Sweetwater River settles to the bottom within NAVSTA piers depending on the strength of the storm event.

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ACRONYMS AND CHEMICAL NAMES

ADCP	Acoustic Doppler Current Profiler
APDC	Ammonium pyrolidine dithiocarbamate
Ag	Silver
As	Arsenic
ASTM	American Society for Testing and Materials
AVS	Acid Volatile Sulfide
BFSD	Benthic Flux Sampling Device
BMPs	Best Management Practices
BPTCP	Bay Protection and Toxic Cleanup Program
CBSE	California Bureau of Sanitary Engineering
Cd	Cadmium
CP-MS	Coupled Plasma-Mass Spectrometry
Cr	Chromium
CSWRCB	California State Water Resources Control Board
Cu	Copper
CVAA	Cold Vapor Atomic Absorption
CVAF	Cold Vapor Atomic Fluorescence
DBMS	Database Management System
DCM	Dichloromethane
DDT	Dichlorodiphenol trichloroethane
DFM	Diesel Fuel Marine
DNA	Deoxyribonucleic acid
EDX	Electron Dispersive X-Ray Fluorescence Spectrometry
EMC	Event Mean Concentrations
EPA	Environmental Protection Agency [U.S.]
ERL	Effects Range Low
ERM	Effects Range Median
Fe	Iron
FPXRF	Field Portable X-Ray Fluorescence
GC/ECD	Gas Chromatography/Electrolytic Conductivity Detector
GC/MS	Gas Chromatography/Mass Spectrometry
GFAA	Graphite Furnace Atomic Absorption
GIS	Geographic Information Systems
HAA	Hydride Generation Flame Atomic Absorption
$HClO_4$	Perchloric Acid
HF	Hydrofluoric Acid
Hg	Mercury
HNO_3	Nitric Acid
HPLC	High Performance Liquid Chromatography
IC	Inhibition Concentration
IC_{50}	Concentration at which the Responses of 50% of Test Organisms are Inhibited
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
IRP	Installation Restoration Program
LC	Lethal Concentration
LC_{50}	Concentration at which 50% of Test Organisms are Lethally Affected
Max HQ	Maximum Hazard Quotient
MCON	Military Construction
MDL	Minimum Detection Limit

Mn	Manganese
Na_2SO_4	Sodium Sulfate
NASSCO	National Steel Shipbuilding Company
NAVFACENGCOM	Naval Facilities Engineering Command
NAVSTA	Naval Station San Diego
NAVSTADB	San Diego Naval Station Database
NCCOSC	Naval Command, Control and Ocean Surveillance Center (currently SSC San Diego)
Ni	Nickel
NS&T	National Status and Trends
NOAA	National Oceanic and Atmospheric Administration
NOEC	No Observable Effect Concentration
NPDES	National Pollutant Discharge Elimination System
NRaD	NCCOSC Research, Development, Test and Evaluation (RDT&E) Division (currently SSC San Diego)
OSI	Organism-Sediment Index
P	Probability value
PAH	Polycyclic Aromatic Hydrocarbon
Pb	Lead
PCB	Polychlorinated Biphenyl
POL	Petroluem, oil, lubricants
PWC	San Diego Navy Public Works Center
RDBMS	Relational Database Management System
RPD	Redox Potential Discontinuity
RSE	Removal Site Evaluation
SAIC	Science Application International Corporation
SC	Static Controls
SDGE	San Diego Gas & Electric
SDIWQR	San Diego Interagency Water Quality Control Board
SEM	Simultaneously Extracted Metals
Si	Silicon
SI	Site Investigation
SOD	Sediment Oxygen Demand
SPI	Sediment Profile Imaging
SSC San Diego	Space and Warfare Systems Center San Diego
SVOC	Semi-Volatile Organic Compounds
SWDIV	Southwest Division, Naval Facilities Engineering Command
TOC	Total Organic Carbon
TPAH	Total Polycyclic Aromatic Hydrocarbon
TPH	Total Petroleum Hydrocarbons
TSS	Total Suspended Solids
TRIM	Tidal Residual Intertidal Mudflat
TRIM-2D	Depth-Averaged Tidal and Residual Circulation Model
USACoE	U.S. Army Corps of Engineers
USDN	United States Department of the Navy
USGS	U.S. Geological Survey
UV	Ultra Violet
WEA	Weight of Evidence Approach
WQC	Water Quality Criteria [U.S. EPA]
XRF	X-ray Fluorescence
Zn	Zinc

UNITS OF MEASURE

°C	degrees Celsius
cm	centimeter
$cm \cdot s^{-1}$	centimeter per second
$cm \cdot y^{-1}$	centimeter per year
ft	feet
$g \cdot cm^{-2} \cdot yr^{-1}$	gram per square centimeter per year
$kg \cdot yr^{-1}$	kilogram per year
km	kilometer
km^2	square kilometer
lbs	pounds
m	meter
$mg \cdot kg^{-1}$	milligram per kilogram
$mg \cdot L^{-1}$	milligram per liter
$mL \cdot L^{-1}$	milliliter per liter
mm	millimeter
$m \cdot s^{-1}$	meter per second
$m^3 \cdot d^{-1}$	cubic meter per day
$mt \cdot year^{-1}$	metric ton per year
$ng \cdot g^{-1}$	nanogram per gram
$ng\ m^2 \cdot day^{-1}$	nanogram per square meter per day
ppb	part per billion
ppm	part per million
psu	practical salinity unit
$\mu g \cdot g^{-1}$	microgram per gram
$\mu g \cdot L^{-1}$	microgram per liter
$\mu g \cdot m^{-2} \cdot day^{-1}$	microgram per square meter per day
µm	micron
$\mu mole \cdot g^{-1}$	micromole per gram

1. INTRODUCTION

The objective of this project was to provide an assessment of sediment quality in the area of Naval Station San Diego (NAVSTA). The study focused on two issues: (1) the characterization of sediments including chemical levels, extent, and related ecological measurements, and (2) the evaluation of processes that control the levels, transport, and biological exposure of any potential chemicals of concern. Sediments were characterized based on a range of physical, chemical, and biological testing. Processes evaluated included chemical sources, sediment transport, sediment-water exchange, and degradation. As part of the project, new assessment technologies were demonstrated and validated alongside traditional methods.

The study was limited to evaluation of sediment quality, and processes acting on those sediments, for the region offshore from NAVSTA. The spatial limits of the study area extended approximately from the Sweetwater River on the south, to the Coronado Bridge on the north, and from the NAVSTA shoreline on the east to the Silver Strand on the west (see figure 1). The data examined included all readily available physical, chemical, and biological studies from the past 10 years, along with significant new data collected as part of this study (see stations in figure 1). Results from many previous studies were incorporated into the assessment to provide the most comprehensive evaluation possible. While biological effects and bioaccumulation in marine organisms were evaluated, potential food chain effects and human health concerns were not. In 1990, the San Diego Association of Governments (SANDAG) completed a comprehensive study of human health issues for San Diego Bay and found minimal risk to human health from direct contact or consumption of seafood from San Diego Bay.

San Diego Bay is home port to a substantial fraction of the Navy's fleet, most of which are directly supported by NAVSTA. Supporting the large number of ships and facilities associated with the Fleet requires a balance between the Navy's requirements and the natural, recreational, and commercial uses of the bay. In general, historical and ongoing activities from both Navy and non-Navy sources have led to the loading of bay sediments with a range of chemicals (NOAA, 1991). For the Navy to minimize the potential impacts of its operations on the bay, the current status of chemical levels must be documented, and the sources and processes that control these levels must be characterized.

Section 2 describes the general approach used in the study, and specific background data on historical contamination and general conditions within the bay are reviewed in section 3. Section 4 describes the data management component of the study, including development of a database repository for studies relevant to Navy sediment quality issues in San Diego Bay. Section 5 describes the sediment quality characterization including physical, chemical, and biological analyses. Studies of processes that regulate sediment quality in the NAVSTA region are described in section 6, including source characterization, loading budgets for chemicals of concern, chemical remobilization, and transport and fate modeling. In section 7, conclusions regarding all lines of evidence are summarized to provide guidance towards effective risk management of sediments in the NAVSTA region.

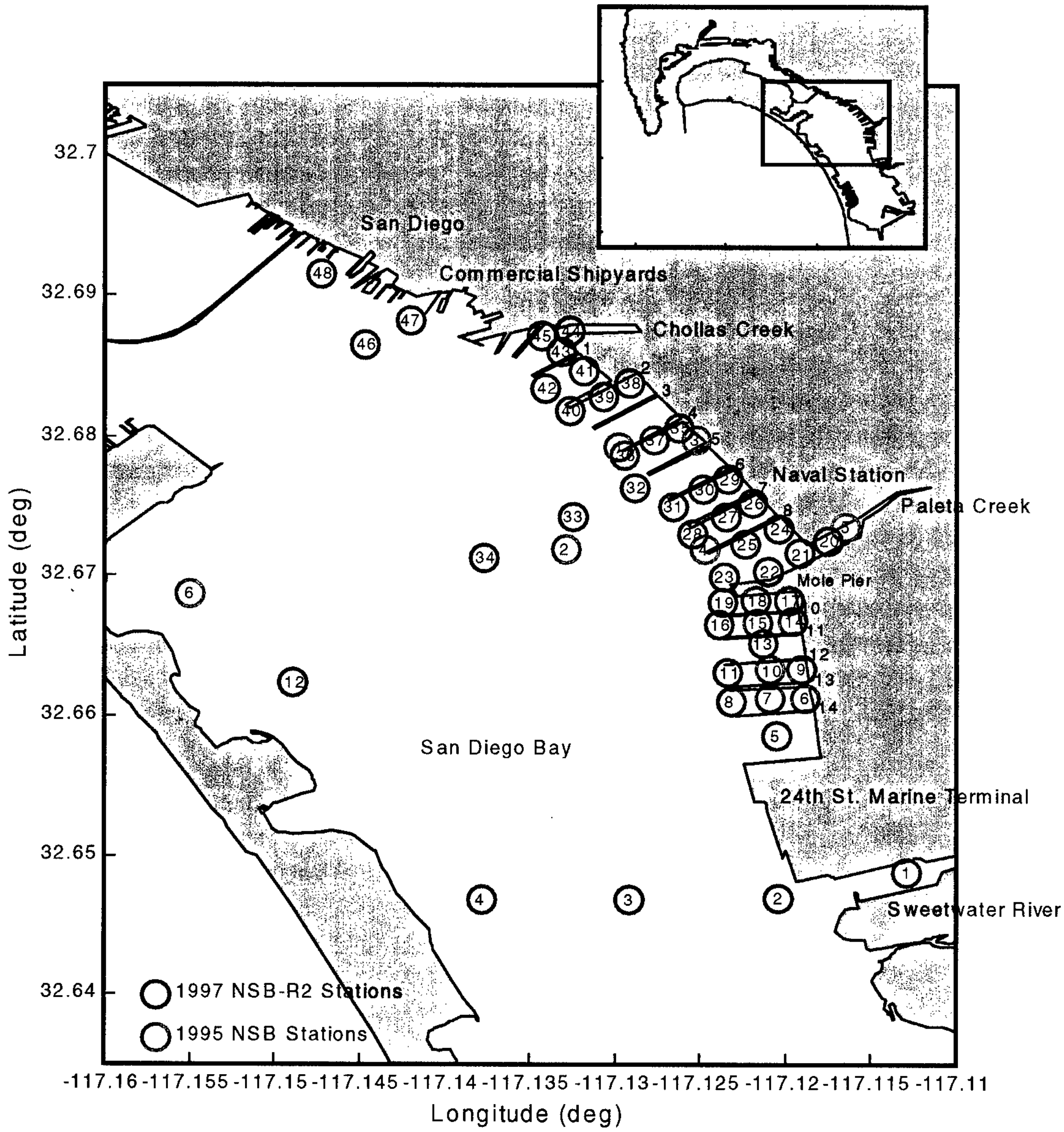

Figure 1. Location of the study stations used in this project for detailed assessment of sediment quality characteristics and sediment process studies. Red circles indicate stations that were sampled for detailed physical, chemical, and biological characterization during the 1995 survey. These stations were also re-sampled during the 1997 survey when infaunal bioaccumulation and biomarker studies were repeated. Blue circles indicate the location of the additional stations sampled during the 1997 survey to provide increased spatial resolution of chemical distributions in the sediments. Numbers along the shoreline at Naval Station refer to the pier numbers.

2. TECHNICAL APPROACH

2.1 CONCEPTUAL FRAMEWORK

The conceptual framework for this study was developed based on the two primary objectives of characterizing existing sediment contamination, and characterizing the processes that control contaminant levels. The technical components of the study were broken down into three categories including:

- Data Management
- Sediment Characterization
- Sediment Processes

Figure 2 summarizes the relationship between these components and the rationale for including them in the study. The approach for each of the components and their relationship to the overall objectives is outlined below.

2.1.1 Data Management

During the initial stages of the project, it became apparent that previous investigators had already collected a large amount of information. Unfortunately, no common data format or repository existed for the large number of prior sediment studies. Therefore, a decision was made in the beginning to focus a large effort on developing an overall data management strategy. Under this strategy, existing and future data sets could be compiled and made easily available for addressing ongoing concerns regarding contamination at Navy sites in San Diego Bay. The specific goals for the NAVSTA data management task included:

- Compiling a historical baseline for the spatial and temporal distribution of chemicals in San Diego Bay;
- Storing measurement data collected as part of the current project;
- Sharing data among the investigators working on different aspects of the research objectives;
- Accessing the measurement and supporting data directly from typical software applications;
- Ensuring the quality of both historical and current project data, in terms of completeness, consistency, and accuracy; and
- Archiving both the historical and current project measurement data.

The technical approach for the development of this data management capability included:

- Developing a logical data model for managing environmental measurement and supporting data;
- Implementing a relational database from the data model;
- Inputting measurement data from historical and project sources into the database;
- Formulating queries and other applications for accessing the data in the database; and

- Planning for the long-term maintenance of the database.

A more complete description of the development of the NAVSTA database is included in the Data Management section. Additional details have been discussed in detail elsewhere (Key *et al.*, 1995; Key, 1996).

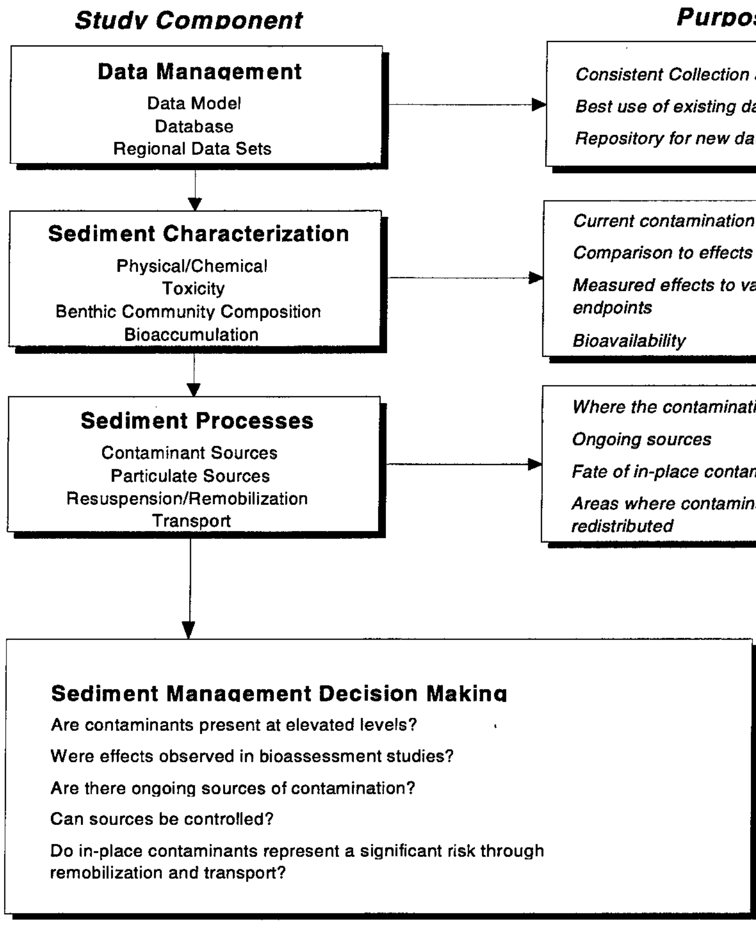

Figure 2. Relationship between study components and the purpose for their inclusion in the study.

2.1.2 Sediment Characterization

Many approaches have been developed or proposed for the characterization of sediment quality. MacDonald (1996) recently reviewed the most noteworthy approaches. There are currently no numerical sediment quality criteria that apply directly to the sediments of San Diego Bay. The State of California has yet to adopt sediment standards. The states of Washington and Florida have recently proposed numerical guidelines for the assessment of sediment quality (MacDonald, 1996). The approach adopted here was adapted from the "weight of evidence approach" (WEA) proposed by Long and Morgan (1995) and utilized by the State of Florida [1]. WEA allows for multiple lines of investigation to be accounted for, and weighted, according to their importance in estimating ecological risk. In addition, avail-

able water quality criteria were applied to assess measured pore water concentrations collected from interstitial spaces within the sediment.

The basic elements of the WEA approach include the characterization of sediment chemistry, toxicology, and benthic community composition as distinct lines of evidence. Following the Florida model, chemical levels are first evaluated to see if evidence of contamination is present. If insufficient chemistry data are available, further measurements are carried out. Chemical levels are then normalized and compared to background levels to assess natural versus anthropogenic, or man-made, origin. If elevated levels attributed to anthropogenic sources are present, biological effect studies are implemented. This process can potentially consist of chemical characterization, biological effect characterization, bioassay studies, and in-situ bioaccumulation and biomarker studies. Study results are presented in the Sediment Characterization section, where approaches and methods for individual study components are described. The results of this study are intended as a guide toward evaluating the available lines of evidence, and not a final determination of risk or risk management outcomes.

2.1.3 Sediment Processes

Initial review of existing studies for NAVSTA indicated that a large amount of chemical and biological information had already been collected in the region. The primary data gaps identified were the processes that lead to and control the contamination levels in the sediments. Thus, a major component of the work performed in this study focused on trying to understand what processes led to the current contamination levels, and what processes control biological exposure and response, as well as remobilization and transport of the chemicals.

To fully evaluate the potential effects of naval activities in San Diego Bay, potential sources from Navy and non-Navy inputs were considered along with their locations, strengths, and chemical and toxicological character. Existing source records were examined for shipboard oily waste discharges, antifouling hull coating release rates, hull cleaning processes, fuel spills, etc. Additional studies evaluated other potential sources of pollution into the Bay, including non-point runoff, streams and rivers, sediment exchange, and pier-piling leachate. An effort was made to construct a current budget for the sources of each chemical of concern in the NAVSTA region.

Chemical remobilization from sediments was also examined as both a potential source, and a process that acts to redistribute chemicals. The two primary remobilization processes evaluated were sediment-water exchange and ship-driven resuspension. The first process was evaluated to estimate the relative source loading and exposure potential from sediments, and to measure the rate at which natural processes remove chemicals from the sediments. The second process was examined to determine the extent and frequency of resuspension events related to ship movements, and the desorption of chemicals from sediments following resuspension. Field measurements of the extent and concentration of sediments resuspended during ship movements were implemented and used as input to a modeling effort to predict the transport of sediments.

The transport and fate modeling component of the study served two purposes. The first was to address specific questions about the transport and fate of contaminated sediment in the NAVSTA region. The second purpose was to develop a general-purpose hydrodynamic transport model that could be applied to various Navy water/sediment quality issues. Baseline data on sources, sediment characteristics, and hydrodynamic and meteorological forces

were collected and synthesized to provide the inputs required to run and validate the Tidal Residual Intertidal Mudflat (TRIM) model for the NAVSTA region, in particular, and for San Diego Bay, in general. The effort included registration of sediment type and existing chemical distribution data into the TRIM visualization effort. All data were converted to geographical information system (GIS) form for compatibility with Southwest Division, Naval Facilities Engineering Command (SWDIV) and the individual activities. Specific applications of the validated TRIM model in this study included simulations of circulation, bottom shear, sediment transport, transport of sediments resuspended by ships, and transport of chemicals introduced by stormwater.

2.1.4 Overall Characterization

Conclusions from the tasks described above were combined to provide an integrated view of both the current status of sediment quality in the NAVSTA region, and the processes that act to control it. Factors considered in characterizing sediment quality, and the potential risks associated with in-place sediment contaminants, include chemical levels, observed biological effects, sources, remobilization, partitioning, transport, and degradation. A composite framework was developed as a means of chemicals of concern in NAVSTA sediment, incorporating issues of ongoing sources, transport and mobility, as well as traditional measures of chemical levels and biological effects (figure 3). Recommendations were then prepared on the basis of this evaluation, with an emphasis on addressing the specific sediment quality issues outlined in figure 2. As stated previously, the results of this study are intended as a guide towards evaluating the available lines of evidence, and not a final determination of risk or risk management outcomes.

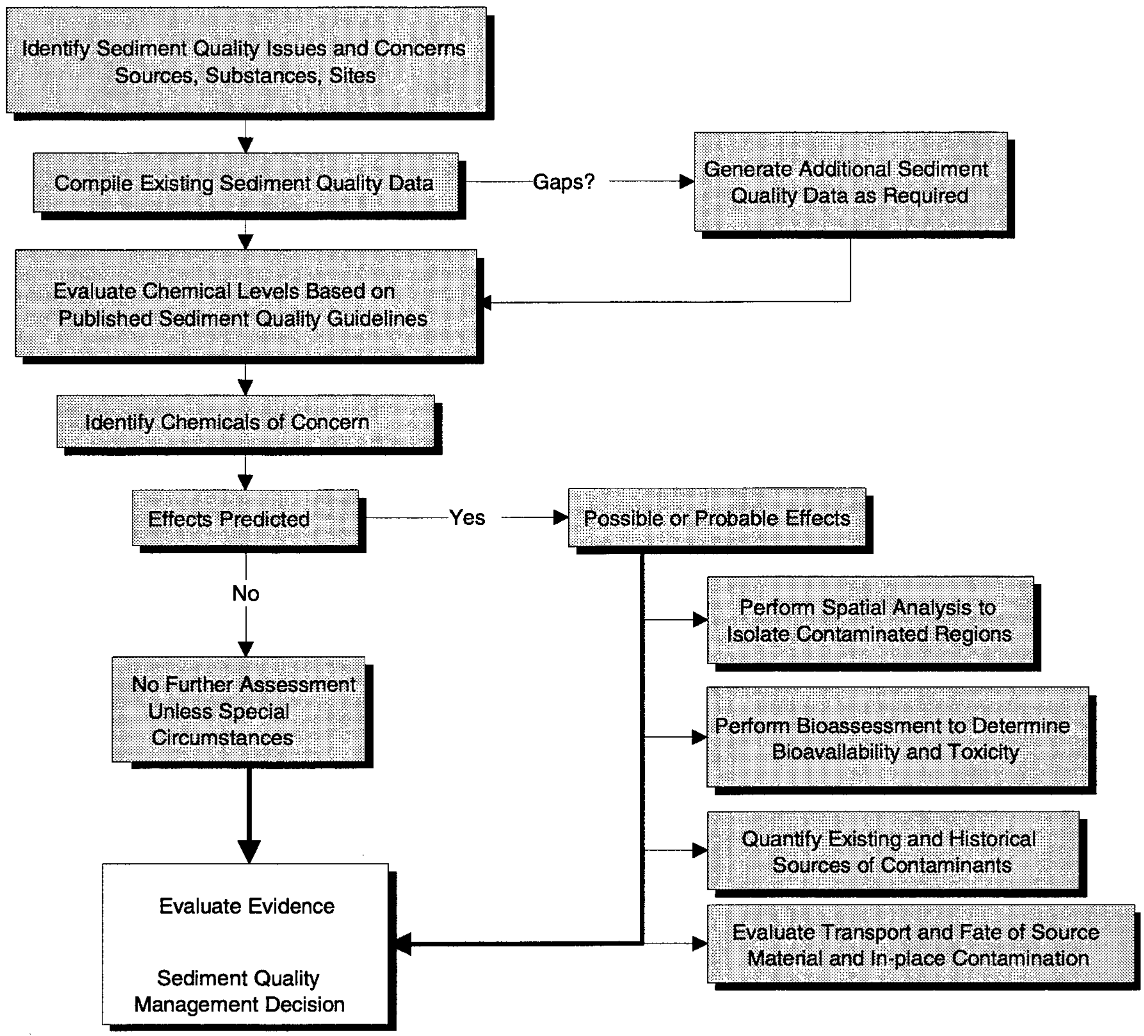

Figure 3. Composite sediment quality assessment framework used for the NAVSTA study including traditional measures of chemical levels and biological effects, as well as measures of chemical sources and transport. Shaded boxes indicate components where studies were performed as part of this project.

3. HISTORICAL AND PHYSICAL SETTING

3.1 GENERAL DESCRIPTION

San Diego Bay is a semi-enclosed, crescent-shaped embayment bordering the city of San Diego on the southernmost coast of California. The bay, which is oriented in a mostly northwest–southeast direction, opens to the Pacific Ocean at Point Loma (see figure 4). The bay is characterized by two geographic regimes: the region south of the Coronado Bridge, commonly referred to as south bay or back bay, and the region north of the bridge to the bay's connection to the Pacific Ocean at Zuniga Point, considered north bay. The bay, bordered by the cities of San Diego, National City, Chula Vista, and Coronado, with an estimated total population of 1.2 million, supports a large number of recreational, commercial, and naval facilities. Small boat harbors ring the bay, many having been formed through dredge and fill projects. The larger ones include Shelter Island, Commercial Basin, Harbor Island, and Glorietta Bay. These harbors contain most of the commercial boating and recreational facilities on the bay. Naval facilities fronting the bay include Submarine Base San Diego and SSC San Diego research laboratories on Point Loma, North Island Naval Air Station in mid bay, the Naval Amphibious Base, and NAVSTA in south bay. The largest of these with regards to ship activity is NAVSTA, supporting a fleet of approximately 50 ships. The North Island Naval Air Station is homeport to two aircraft carriers.

3.2 MORPHOLOGY

The bay is roughly 25 km along its axis and varies in width from 0.5 to 4 km. The area of the bay is approximately $4.1 \cdot 10^7$ m^2 at mean lower low water (Peeling, 1974) with an average depth of approximately 5 m. This gives a water volume of approximately $2.2 \cdot 10^8$ m^3. In general, the south bay is broader and shallower than the remainder of the bay. Water depths there range from 1 to 4 m outside of the main shipping channel, which is dredged to a depth of about 12 m. Depths generally increase toward the entrance, reaching a maximum depth of about 21 m near Ballast Point. The main shipping channel follows the axis of the bay from the mouth to the Coronado Bay Bridge. South of the bridge, the channel hugs the eastern shoreline to its southern limit just below the entrance of the Sweetwater River. Creeks and rivers feed fresh water and particulate material into San Diego Bay primarily in winter. These include, in order of decreasing drainage area: Sweetwater River (540 km^2), Otay River (360 km^2), Chollas Creek (70 km^2), and Paleta Creek (~10 km^2) (Conway and Gilb, 1989). All discharge into the south bay is in close proximity to NAVSTA with the exception of the Otay River. Other sources of fresh water and particulates to the bay include non-point source runoff during winter storms and incidental amounts of runoff from agricultural and landscape watering. Ground water is not a significant source of fresh water to the bay (Peeling, 1974).

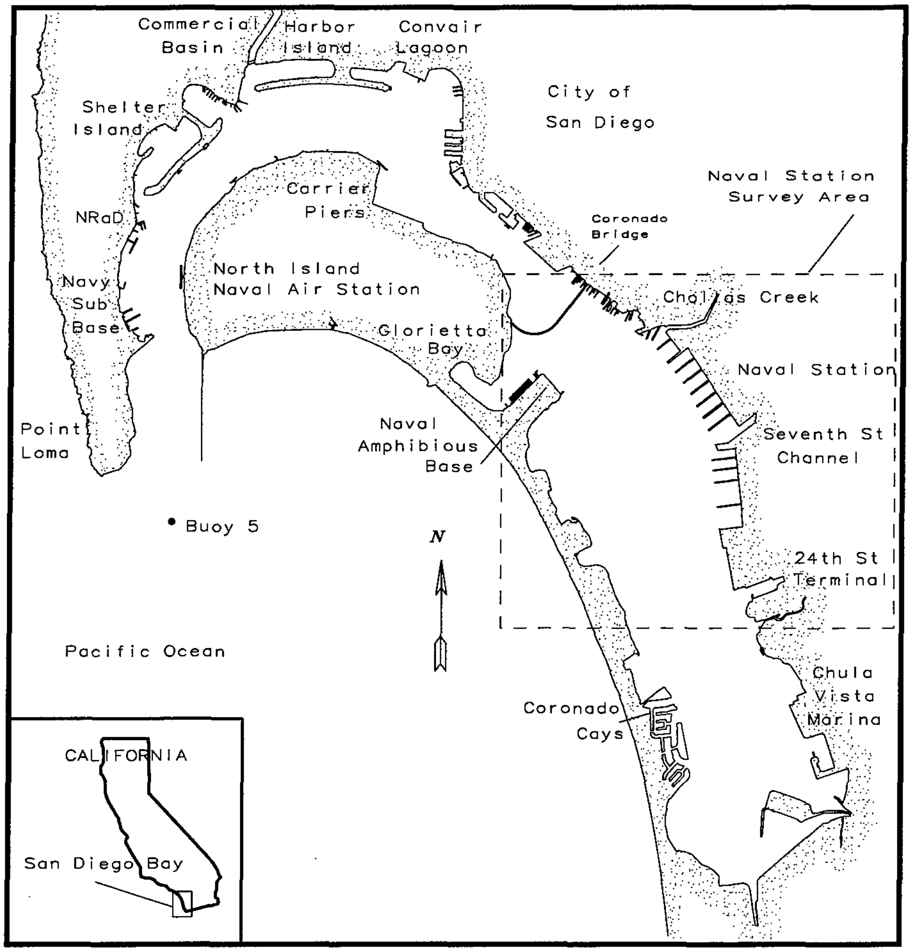

Figure 4. San Diego Bay general study area. The outlined region is the NAVSTA survey area.

3.3 CLIMATE

The climate of the San Diego region is characterized as semi-arid. Annual rainfall is limited to an average of 25 cm and occurs almost exclusively between November and April. Rainfall is primarily associated with episodic storm events resulting in a highly fluctuating nature to the freshwater inflow to the bay. Evaporation exceeds precipitation during spring, summer, and fall and totals approximately 160 $cm \cdot y^{-1}$ [2].

Average air temperature measured at San Diego's Lindbergh Field International Airport ranges from 14.4 to 22.2°C throughout the year. Because of the airport's proximity to the coast, the temperatures measured at the airport are moderate relative to those measured at inland locations. However, for the most part, these measurements are representative of the air temperatures influencing San Diego Bay.

Typical winds are from the west (onshore) at average speeds of about 5 $m \cdot s^{-1}$. There is a strong diurnal component to the wind most of the year; calmer winds in the evenings and mornings give way to stronger afternoon sea breezes. Strong onshore winds also occur episodically during winter storms. During periods when exceptionally high pressure develops over the deserts, commonly in September and October, strong offshore winds occur. These winds, termed "Santa

Anas," result in exceptionally low (<20%) relative humidity and very high (>30°C) air temperatures.

3.4 HYDROGRAPHY

Currents within the bay are dominated by a mixed diurnal-semidiurnal tidal forcing with a dominant semidiurnal component (Peeling, 1974). The tidal range from mean lower-low water to mean higher-high water is about 1.7 m with extreme tidal amplitudes of about 3 m [3]. In general, tidal currents are strongest near the mouth, with maximum tidal speeds of about 50 to100 $cm \cdot s^{-1}$ (Largier, 1995). Higher velocities are also found at the narrower portions of the bay just north of the Coronado Bay Bridge. In general, the current direction lines up with the axis of the bay.

Bay water temperatures range from about 14 to 25°C throughout the year (Largier, 1995; Lapota et al., 1993). This range in temperature is also observed from the mouth into the south bay in summer [3]. This axial gradient exists to a lesser extent in winter, with temperatures increasing from about 14°C at the mouth to about 16°C in south bay. For the most, part bay waters are vertically well-mixed throughout the year. However, summer heating and the intrusion of cool ocean water at the entrance results in vertical stratification, particularly at the mouth [3]. There is an additional year-round input of warm water from the San Diego Gas and Electric (SDGE) power plant at the southernmost portion of the bay. The plant takes in and discharges roughly $2.2 \cdot 10^6\ m^3 \cdot d^{-1}$ of sea water for cooling purposes. The discharge water averages approximately 5°C above intake water temperatures [4].

As a result of the high evaporation, the south bay develops high salinity concentrations, or becomes hypersaline, in summer, with salinities reaching as high as 38 practical salinity units (psu), compared to ocean water of about 33 psu. Common values are 33.3 psu at the mouth, increasing to about 35.5 in the south bay . Conversely, runoff during winter results in lower salinities in south bay. Common winter salinity values decrease from 32.8 psu at the mouth to 30.4 psu in the south bay [5]. Very low salinity values (22.2 psu) have been observed at the sea surface during exceptionally high runoff periods off of the Sweetwater River [5].

There are several factors that influence the density structure in San Diego Bay. These include variations due to tidal mixing and horizontal movement, thermal discharges to the bay, and changes in heating, evaporation, and rainfall. Largier (1995) has shown that the seasonal cycle of density within the bay follows a predictable pattern characteristic of "Mediterranean"-type estuaries. In the late spring and early summer, the density of the bay water is controlled by heating that occurs more rapidly than evaporation. In the late summer, the water in the inner bay becomes hypersaline due to evaporation. As this hypersaline water cools during the fall, its density increases. Winter rains then lower the salinity and for a short period the density may be controlled by freshwater inflows.

The mechanism by which bay water exchanges with the ocean is critical to the flushing of the bay. At the mouth, flushing results from "tidal pumping," an asymmetry between a jet outflow and a sink inflow in the region immediately seaward of the mouth (Largier, 1995). The effect of tidal pumping is a relatively high tidal exchange rate at the mouth in which as much as 60 percent of the water brought in on flood tide is new ocean water (Chadwick et al., 1996). Flushing is, thus, very effective at the mouth, with the residence time of water on the order of a day. Moving in from the mouth, there is a reduction in tidal exchange rates and

residence times of water increase from about 5 to 20 days in mid-bay to over 40 days in south bay.

3.5 WATER QUALITY

Parameters commonly measured to assess water quality include dissolved nutrients, dissolved oxygen, pH, water clarity, chlorophyll *a*, and coliform bacteria. Most of these have been measured throughout the bay over the last several years [3.5]. Additionally, ultraviolet (UV) fluorescence has been used as a chemical tracer of water mass mixing in San Diego Bay [3].

Results of these measurements suggest that dissolved nutrients such as phosphate and silicate are at a maximum in the south bay during winter as a result of runoff (Lapota et al., 1993). Values which range 0.9 to 4 parts per million (ppm) silicon (Si) and 0.02 to 0.3 ppm phosphorus in winter decrease to 0.3 to 1.3 ppm Si and 0.04 to 0.2 ppm phosphorus in summer. The seasonal decrease results from a reduction in inputs and from uptake by phytoplankton for growth. Their distribution through the bay somewhat mimics the input of fresh water, which means they generally decrease from south bay to north bay although plankton uptake can locally alter concentrations.

Dissolved oxygen concentrations in San Diego Bay are typically at or near atmospheric equilibrium levels. Concentrations range from about 4 to 8 $mL \cdot L^{-1}$ seasonally and are typically higher in winter [5]. Higher levels observed in south bay during winter are associated with the inflow of fresh water. The higher oxygen levels may be a result of higher values present in the freshwater inflow or may be a byproduct of the higher generation rates associated with increased primary production observed at that time. Oxygen levels fall off in summer with increasing seawater temperatures and a concurrent decrease in equilibrium levels, although concentrations can be locally altered by plankton production.

The distribution of seawater pH in San Diego Bay is fairly uniform throughout the year [5]. Values range from about 7.9 to 8.1 both spatially and seasonally. Like oxygen, pH can be altered locally by phytoplankton with higher pH resulting from higher productivity. Thus, the higher values of pH tend to be associated with runoff in south bay and with open-ocean water intrusion at the mouth.

Light transmission measurements can be used to determine the amount of particles suspended in the water column that are not originating from living organisms, or non-biogenic. These measurements are, thus, a good gauge of water clarity. In general, transmission levels or clarity decrease as a function of distance from the mouth into south bay. When calibrated against the estimates of the actual weight of the dry material within a given volume of sea water (known as gravimetric measurements), transmission values typically indicate a background particulate load of about 2 to 4 $mg \cdot L^{-1}$ at the mouth, increasing to about 12 to 19 $mg \cdot L^{-1}$ in south bay. This occurs as a result of resuspension of bottom sediments in the shallow waters of south bay from tide and/or wind influences, and from resuspension associated with ship movements in and around NAVSTA (Hyman et al., 1995). There is also a large input of particulate material with freshwater runoff in winter in south bay.

Chlorophyll *a*, a measure of the standing stock of phytoplankton present in the bay, ranges from 0.2 to 25 $ug \cdot L^{-1}$ with maximum values measured in south bay during winter when high nutrients are introduced with runoff [5]. These levels drop in summer to background levels

of 1 to 2 $ug \cdot L^{-1}$. In general, these levels are considerably higher than those observed in the adjacent open ocean. The distribution of chlorophyll *a* in the bay is controlled by a balance of factors including temperature, nutrients, and light levels, resulting in a distribution that is quite variable and somewhat patchy.

When sewage was discharged into San Diego Bay prior to 1964, fecal coliform counts as high as 82 mL^{-1} (bacterial counts) were measured in south bay (Peeling, 1974). With the stoppage of these discharges, fecal coliform counts typically remain below $10 \cdot mL^{-1}$ except possibly during some storm events. These levels are below federal limits for water contact, implying that the bay is generally safe for recreational use.

3.6 BIOLOGY

The biological productivity of San Diego Bay is considerably higher than the surrounding Pacific Ocean, which is more characteristically low in nutrients. Primary production is at least a factor of 10 higher in the bay relative to the surrounding ocean waters, presumably as a result of nutrient loading from near-shore sources. The higher production of organic matter in the bay can, therefore, support a relatively higher biomass.

Marine habitats in San Diego Bay provide shelter and other life support for 66 kinds of finfish, 48 of which are important commercially or recreationally (Needham, 1983). The bay supports an additional 40 more species that thrive in Pacific waters outside the bay. The most abundant and widely distributed species in the bay include anchovy, Pacific bonito, black croaker, bass, California halibut, and opaleye. Although most fish species are evenly distributed throughout the bay, there is some variation in either type or abundance from south to north bay. Over 200 species of invertebrates also thrive in the bay, 22 of which are commercially or recreationally important. The most abundant are the California spiny lobster, rock crab, lined shore crab, littleneck clams, chione cockles, rock scallop, clams, and mussels. There are also over 72 species of birds inhabiting the bay such as loons, grebes, blue herons, white and brown pelicans, egrets, scoters, falcons, sandpipers, terns, and gulls (U.S. Army Corps of Engineers (USACoE), 1973).

Important marine habitats of the bay can be categorized by their depth distribution, bottom type, and/or vegetation. Habitats categorized by depth include the intertidal, shallow subtidal (mean low tide to 5 m), and deep subtidal (5 to 25 m). The shallow subtidal zone constitutes about 58 percent of the bay water surface area while the deep subtidal makes up about 42 percent. The $4.8 \cdot 10^6$ m^2 of intertidal zone, about 10 percent of the bay water surface area, is composed of 54 percent mudflat, 29 percent tidal marsh and salt flats, and 17 percent sandy beach (Needham, 1983). Bottom types include mud, sand, rocky, and combinations of these three. The bottom types of north bay are predominantly coarse grain sands and rocky. Those of south bay are generally mud bottom while those of the central bay are mud and sandy. Marine habitats also include man-made marine structures including pier pilings, floats, riprap, and concrete steel bulkheads.

Important vegetation that alters bottom habitats is the presence of benthic algae including eelgrass. Eelgrass flourishes in clearer, calm water near shore in less than 6 m. There is roughly $1.6 \cdot 10^6$ m^2 of eelgrass coverage in the bay although its distribution varies from sparse patches to very dense growths (Needham, 1983). The single most important habitat for San Diego Bay shellfish is shallow-water eelgrass in a mud/sand bottom in proximity to rocky

shores. The highest diversity of fisheries resources also occurred in regions of eelgrass [6]. For this reason, habitat modifications have usually included planting of eelgrass as mitigation projects.

The diverse marine habitats of San Diego Bay are a rich resource for food, shelter, and nursery grounds for both finfish and shellfish (Needham, 1983). The advantages of nursing in bays has been shown, at least for halibut, to include decreased predation and an increased growth rate because of abundant food sources (Kramer, 1991). While many finfish and shellfish hatch and develop in the shallow areas of south bay and remain permanent residents there, others move out into the deeper waters of the bay or beyond into the Pacific Ocean. In this way, the bay serves to replenish some offshore species by either direct migration or by larval disbursement (Needham, 1983).

3.7 SEDIMENTS

The sediments of San Diego Bay consist primarily of gray, brown, or black mud, silt, gravel, and sand. In general, the grain-size distribution of sediments in north bay is coarser, while those of the south bay are composed more of silt and mud. However, as shown in figure 5, the distribution can vary from this general pattern with some areas almost exclusively sand such as that off North Island and areas that are predominantly silt such as those within Shelter Island (Kram et al., 1989). Within the NAVSTA region of the bay, the clay fraction of the sediments tends to decrease systematically away from the quay walls (Anderson, 1994) and with depth [7]. This distribution is consistent with sources that are principally due to runoff of terrigenous materials following periods of sustained rainfall (Grovhoug et al., 1987) and deposition of the smaller sized particles in the relatively low-flow regions along the piers.

While distribution of sedimentary materials in the bay is reasonably consistent with sources and depositional environment, two processes redistribute them. The first process is dredging that artificially alters areas of high deposition through the wholesale removal of material. The second process is both a man-made and natural process in which sediments are resuspended into the water column and redistributed by currents. Natural resuspension occurs from tidal- or wind-generated currents moving over the bottom in shallow regions such as south bay. Man-made resuspension results from ship propeller wash that occurs primarily during ship movements in and out of pier areas or even in the deeper mid-channel region during the transit of large ships such as carriers (Hyman et al., 1995).

Sedimentary organic carbon concentrations in the bay have been measured in the range of 0.1 to 18 percent although they are most commonly in the 1 to 5 percent range (Kram et al., 1989). In general, the higher organic carbon values tend to be associated with finer grained material (Kram et al., 1989). The source of the organic matter is both *in situ* biogenic originating from living organisms) production and input from the breakdown of the earth's crust. This relatively high organic loading commonly leads to the absence of free oxygen in the sediments within a centimeter of the sediment surface. The presence or lack of oxygen in sediments is an important biogeochemical factor because of the control it exerts on the type of biota (flora and fauna) able to live there and its impact on sedimentary redox (reduction-oxidation) chemistry. The biota and redox chemistry are key components to understanding the processes occurring within sediments.

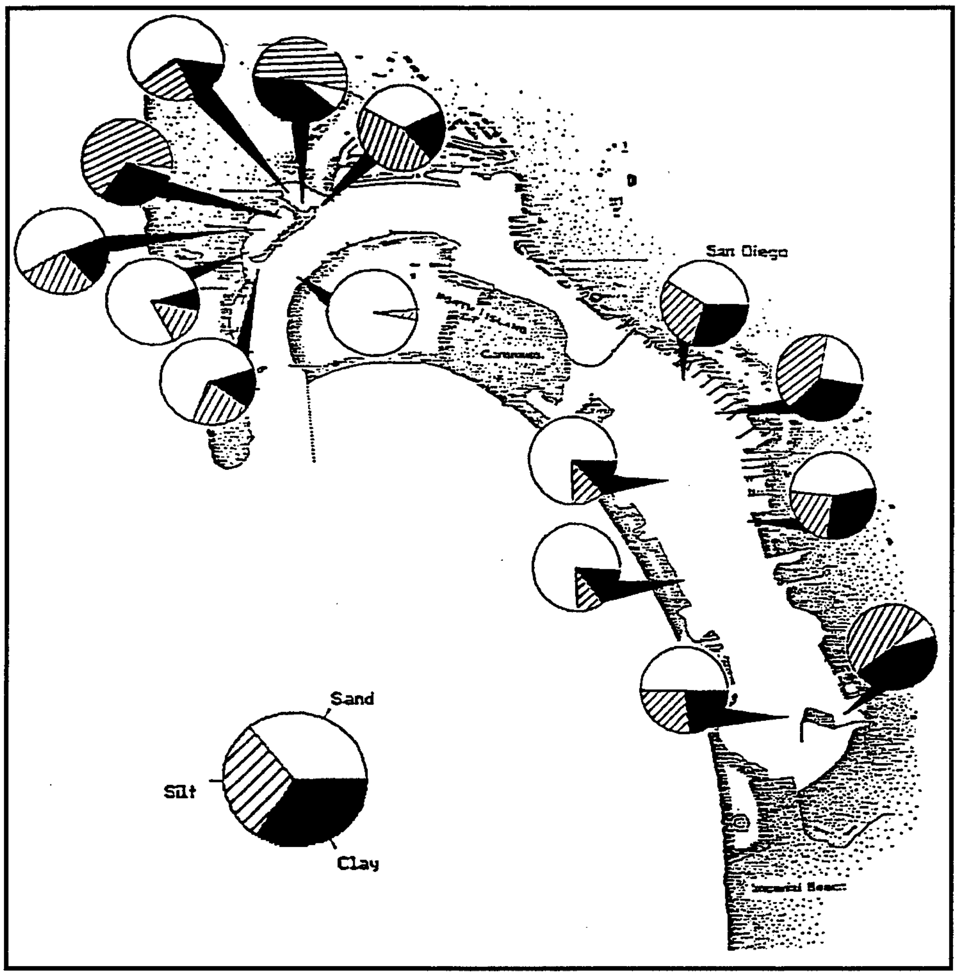

Figure 5. Sediment grain-size distribution in San Diego Bay (from Kram et al., 1989).

3.8 PAST AND PRESENT POLLUTION IN SAN DIEGO BAY

Sediments are typically the final repository for solid particulate material produced in or reaching the bay. As such, they are also the typical resting-place for many contaminants. Therefore, they provide an historical, albeit imprecise, record of the sources, distribution, and sinks of contamination. In San Diego Bay, these sources have varied over time. Past and present pollution sources have included sewage, industrial (commercial and military) wastes, ship (commercial, pleasure craft, and military) discharges, urban runoff, and accidental spills. While chemical distribution is primarily controlled by source locations, hydrography (flow and behavior of a water body) plays an important role in their transport and ultimate settlement. Redistribution can occur as a result of physical, biological, biochemical, or chemical processes. In the bay this includes processes such as dredging, resuspension, bioturbation (physical disturbance caused by organisms in the sediment), biological uptake, degradation, dissolution or chemical reactions. Therefore, understanding contaminants in bay sediments requires knowledge of past and present sources as well as processes that serve to alter them over time.

3.8.1 Past Pollution Sources in San Diego Bay

San Diego, first claimed by Spain in 1542, was eventually controlled by the United States in 1846. Population at the time was 500. Settlement increased dramatically in the 1880s. Historical reports derived from settlers reveal the Bay's once-pristine nature. Extensive shell debris indicates that early inhabitants were attracted to the Bay by the abundance of shellfish along its shore. The San Diego River was diverted in 1875 to the Pacific Ocean, playing a major role in the amount of freshwater input to the bay (Peeling, 1974). In 1888, water quality degradation began with the completion of the Cuyamaca Dam and 40 miles of sewers, coupled with a sewage reservoir and outfall located in the bay off downtown San Diego. The gradual decline in bay water quality continued over the next half-century as the population increased and the bay became a major harbor for the U.S. Navy and civilian commerce. Bacteriologic sampling in the 1920s and 1940s uncovered water contamination around sewage discharges.

World War II and the Korean War caused a dramatic increase in military activity and manufacturing of aircraft and ships in and around San Diego Bay. The population of San Diego increased abruptly to over 400,000 during this period, causing the failure of the overloaded sewage collection and treatment facilities. By 1943, raw or improperly treated sewage was being discharged into the bay from 15 outfalls. During the post-war period, more than 50 million gallons per day of sewage and industrial wastes were disposed of in the bay. At the same time, the bay was receiving untreated industrial discharges from five fish canneries, a large rendering operation, a kelp processing plant, four aircraft manufacturing plants, several shipyards, and three U.S. naval installations.

Water sampling in the 1950s showed that the bay had become contaminated due to the heavy loading of domestic and industrial wastes. Dissolved oxygen had declined to about half of the normal levels in the central bay areas and to near zero levels in some places. Pathogenic and sewage indicator bacteria (coliforms) were routinely isolated from the Bay at significant levels. In 1955, the State Board of Public Health and San Diego Department of Public Health declared much of the Bay contaminated, and the Department of Fish and Game determined that only small areas of the Bay contained native fauna. Excess hydrogen sulfide production was caused by uncontrolled plankton blooms and subsequent high organic loading to the sediments. This resulted not only in offensive odors near the Bay but also led to a ship corrosion rate twice that experienced at sea. Bacteriologic sampling showed that most of the Bay was unfit for recreational swimming or the taking of shellfish. The effects of industrial waste could not be adequately measured during this period because of the masking effects of the sewage. A 1951 report to the Regional Board [8] indicated that one of the aircraft manufacturing plants routinely discharged untreated spent plating, anodizing, and some stock solutions into the Bay at a rate of 30,000 gallons per day. Many other industries utilized similar disposal methods.

By 1963, a massive collection, treatment, and ocean sewage disposal system was brought online by the City of San Diego. As sewage discharge to the bay ended, San Diego Bay, once one of the most polluted harbors in the world, was perceived in the second half of the 1960s as one of the cleanest. The sewage sludge deposits on the bottom that covered the eastern shore gradually disappeared and dissolved oxygen levels returned to normal. This change resulted in a return of native fish and shellfish species, as well as the recolonization by valuable plants needed by marine life. The removal of the sewage from the San Diego Bay, which had once caused such a severe threat to public health, allowed the Bay to become a valuable recreational resource.

The dredge and fill history of the bay has occurred since the 1880s. Since then, roughly 90 percent of available marshlands and 50 percent of intertidal lands have been reclaimed (Peeling, 1974). Particularly intensive bay dredging activity occurred during 1941 to 1945 to accommodate Navy operations. Much of the bay was deepened during that period. Main channel dredging adjacent to NAVSTA was also conducted by the U.S. Army Corps of Engineers (USEPA/USACoE) in 1946, during 1964 through 1966, and in 1975 (USDN, 1992a). In addition, the Navy dredged that portion of the channel from downtown to NAVSTA subsequently in 1987 (SDUPD, 1991, as cited in USDN, 1992a). Extensive dredging was also implemented in shoreline areas in 1942, 1951, 1952, 1956, 1964, and 1975. Smaller dredging projects were completed in 1955, the late 1960s, the early 1970s, 1985, and 1987 (USDN, 1992a).

3.8.2 Present Pollution Sources in San Diego Bay

Current sources of pollution to San Diego Bay listed by the San Diego Interagency Water Quality Panel (SDIWQP) in its San Diego Bay 1989/1990 Report include: underground dewatering, industries on the bay and upstream from the bay, marinas and anchorages, U.S. naval installations, underwater hull cleaning and vessel antifouling paints, and urban runoff. In varying degrees these sources have led, and continue to lead, to contamination of some San Diego Bay sediments. Although sewage to the bay has been stopped, both permitted and non-permitted sources (e.g., runoff, spills, etc.) continue to impact the waters and sediments of the bay.

Currently known chemicals in the bay include: arsenic, copper, chromium, lead, cadmium, selenium, mercury, tin, manganese, silver, zinc, tributyltin, polynuclear aromatic hydrocarbons (PAHs), petroleum hydrocarbons, polychlorinated biphenyls (PCB), chlordane, dieldrin, and the polychlorinated pesticide DDT (SDIWQP, 1990). Although these and others have been identified, the extent to which they are of concern has not been conclusively determined. When compared to other similarly sized U.S. harbors, it has been stated that PCB concentrations are some of highest in Southern California, but comparable to other major harbors (Mearns, SDIWQP, 1990). Others such as PAHs and metals, excluding copper, are about average. Although copper is high relative to other harbors, DDT is relatively low.

Although contamination in the bay is not considered a significant public health risk [9], there is a continued concern for the ecological health of the bay. The prevalence of fin erosion in white croaker, barred sand bass, and black croaker as well as liver neoplasms in black croaker have caused concern about the extent of contamination even though the exact cause of the disease is unknown (McCain et al., 1992). Measures of sediment toxicity have also shown varying degrees of mortality or stress on different test species in laboratory studies (SAIC, 1994; SDIWQP, 1990). Contaminant indicator species such as mussels have shown bioaccumulation of a variety of chemicals in the bay that effect growth and reproduction (Salazar and Salazar, 1991).

The combination of a known presence of contaminants, past and continuing sources, and evidence of biological effects has led to concern and an effort to identify the full extent and ecological health of Bay sediments. While numerous independently conducted studies have done well at characterizing some aspects of the problem, they have typically failed to provide a comprehensive view of even limited areas of the bay. For this reason, evaluation of the sediments in and around NAVSTA has included a comprehensive review of historical and

present-day sources of contamination; the transport and fate of chemicals once in the bay; characterization of sediment chemistry, biology, and toxicology; and sedimentary biogeochemical processes. With a full picture of the contaminants, sources, and processes at work within the NAVSTA region, informed decisions can be made as to pollution reduction and management of potential problem areas.

4. DATA MANAGEMENT

4.1 NAVSTA DATA MODEL AND DATABASE

A data model is a description of the types of data a database will hold and how those data will be organized (Simson, 1994). The NAVSTA data model has been designed to represent fully documented primary measurement data (see Key et al., 1995). In this context, a primary measurement is the original quantitative observation made in the field or the laboratory. It includes the parameter that was measured, the quantity of the measured parameter, and the units in which the quantity is expressed. Full documentation adds all the information needed to place a quantitative measurement in context—where the measurement was made, who made it, when it was made, using what method, etc. The overriding design consideration of the NAVSTA data model is that each measurement is represented as a separate record rather than the parameter-by-sample matrix in which measurement data are typically stored.

Each entity specified in the NAVSTA data model was implemented as a table of the same name in the NAVSTA database (NAVSTADB). The other tables in the database provide supporting information about these measurements. All relationships specified in the NAVSTA data model were also incorporated into the definition of the NAVSTADB. These relationships implemented the integrity constraints for the database, including cardinality (i.e., how many?), optionality (i.e., are nulls permitted?), and cascade effects (deleting or updating records among linked tables).

A potential problem when using Access© as the data management system is that it stores all information, including the database definition, the data, and the applications (e.g., custom reports, queries, etc.), in a single computer file. This arrangement can cause problems when the entry of data and the development of applications proceed independently. In anticipation of this problem, the SSC San Diego staff implemented the NAVSTADB using a technique called "separation of code and data." The NAVSTADB was implemented as two related databases. The first, named SD_Bay_D, contains the structure of the database (i.e., tables, columns, relationships, etc.) and the actual data. The second, named SD_Bay, contains all the reports, queries, forms, and other applications developed for using the database. SD_Bay is "attached" to SD_Bay_D such that it appears to contain the same tables, relationships and data as SD_Bay_D. Because the applications developed in SD_Bay are merely attached to the data in SD_Bay_D, it can be updated without overwriting any applications in SD_Bay.

A variety of queries, reports, and forms were developed for using the NAVSTADB. These applications are stored as part of the SD_Bay database. All of these applications can be accessed either through the NAVSTADB "switchboard" interface that runs automatically when the SD_Bay database is opened, or by selecting the appropriate tab in the database dialogue box.

In some instances it is possible to deal with more than one database object (e.g., table, query) through the same Access interface. To simplify dealing with different objects through a common interface, prefixes name the database objects (Leszynski and Reddick, 1994). Custom instructions were also developed to aid the user in navigating the NAVSTADB. These context-sensitive help files are part of the SD_Bay database and can be accessed through the conventional Help button on the Access menu bar.

SSC San Diego continues to upgrade, operate, and maintain the database to support Navy projects in the San Diego Bay region. The database design has been used in similar efforts and has led to the development of a web site on the subject of environmental data management (see http://environ.spawar.navy.mil/ for the announcement of this site). The database supports new applications such as GIS and Web-served data and several other projects at SSC San Diego are adding their own data. To accommodate these new types of data and new applications, a new data model was generated. The new model is implemented as a Microsoft Access® database and the staff is transporting the data, reports queries, etc. to the new database. In parallel, the SSC San Diego staff is implementing the same database structure using the Oracle® database management system (DBMS). This will allow the implementation of true client/server architecture for the NAVSTADB, which will enable both local and remote users to link their applications to the database.

4.1.1 Measurement Data

The priorities established by the project staff for entering past environmental measurements (i.e., historical) data from San Diego Bay into the NAVSTADB were:

- measurements of polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), trace metals, and sediment related parameters such as grain size and total organic carbon (TOC);
- measurements from the sediments and biota;
- measurements from the central and southern portions of San Diego Bay;
- fully documented measurements (e.g., accompanying longitudes and latitudes, methods descriptions, etc.); and
- measurement data in digital form.

Table 1 summarizes the measurement data entered into the NAVSTADB.

Table 1. Summary statistics for the NAVSTADB.

Item	Number of Records
Measurements	151,426
Samples	45,944
Parameters	1,404
Projects	69
Media	32

Table 2 lists some of the major groupings of measurement parameters stored in the NAVSTADB. Since each measurement is stored in the NAVSTADB as a separate record, table 2 can be interpreted to mean, for example, that of the total of 151,426 measurement records stored in the database (table 1), 13,089 of them are for a parameter that is classified as a metal.

Table 2. Number of records by parameter group.

Parameter Group	Number of Records
Biological	68,827
Metals	13,089
Other inorganics	588
PAHs	16,580
PCBs	8,241
Phenol	3,456
Pesticides	9,197
Other organics	5,637
Physical parameters	25,811

Figure 6 is a graph of the number of records in the NAVSTADB by these parameters.

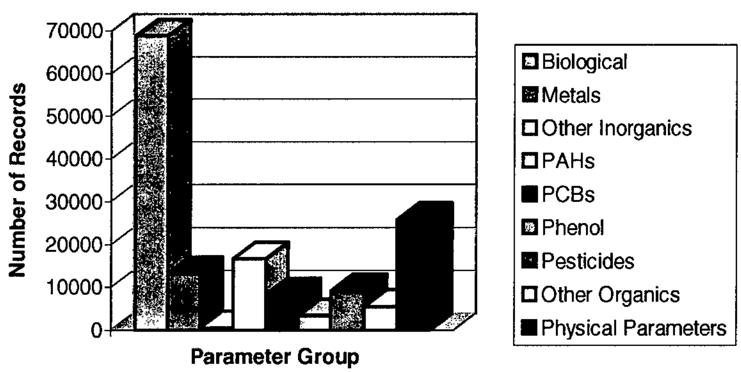

Figure 6. Number of records by Parameter Group.

As noted above, the data entry efforts of the NAVSTA project focused on sediment data in and around NAVSTA. However, when a data set was obtained that contained comparable data from other parts of San Diego Bay, these data were also added to the NAVSTADB. Figure 7 displays the geographic distribution of the numerous sampling stations from which data have been recorded in the NAVSTADB.

4.1.2 Summary Of NAVSTA Data Model and Database

The NAVSTADB design was generalized to support the multidisciplinary nature of the NAVSTA sediment characterization project, with the goal that the database would become a long-term, regional resource. Each entity and relationship specified in the NAVSTA data model was implemented as a table of the same name in the NAVSTADB. To avoid problems arising from independent data entry and application development, the NAVSTADB was implemented as two related databases. SD_Bay_D contains the structure of the database and the actual data, and SD_Bay contains all the reports, queries, forms, and other applications developed for using the database. The NAVSTADB contains approximately 191,149 historical and current measurements of 1,404 parameters including metals, pesticides, PAHs, PCBs, and physical parameters.

SSC San Diego continues to upgrade, operate, and maintain the database and the data model for the support of Navy projects in the San Diego Bay region. Regional data are being added to the database and it is being used to support new applications. In addition, a web site on environmental data management is under development.

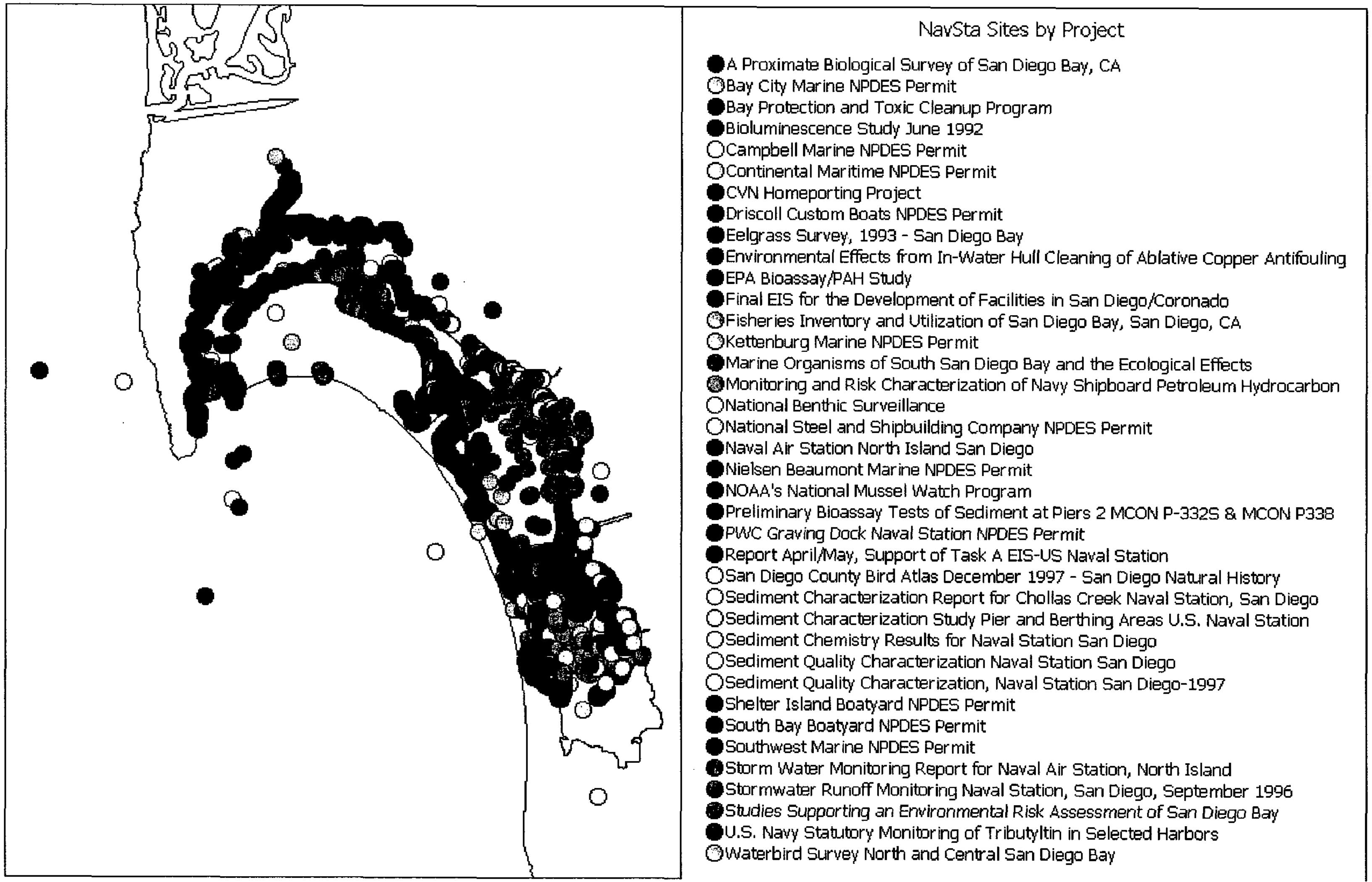

Figure 7. Sample site locations in San Diego Bay.

5. SEDIMENT CHARACTERIZATION

5.1 SEDIMENT (PHYSICAL AND CHEMICAL CHARACTERISTICS)

Physical and chemical characterization of sediments was implemented based on three primary data sources. As described in the data management section, a database comprising sediment quality data from 1985 through 1995 was compiled based on previous studies in the area (figure 7). During 1995, six stations (NSB-1 through NSB-6) situated around NAVSTA were selected for detailed physical, chemical, and biological characterization (figure 1). The stations were chosen based on the historical data set to cover the observed range of physical and chemical properties in the area. In 1997, these six stations were re-sampled in conjunction with bioaccumulation studies, and an additional 48 stations (NSB-R2-1 through NSB-R2-48) were characterized for bulk chemistry to improve spatial coverage, primarily within the NAVSTA piers (figure 1).

To place the physical and chemical properties of the sediments in this study into perspective, one must view the data in relation to other studies. Many other studies have examined the sediments in the NAVSTA area, usually in response to possible dredging (Salazar et al., 1980; SAIC, 1994) or monitoring National Pollutant Discharge Elimination System (NPDES) permit compliance (Southwest Division Naval Facilities Engineering Command, 1994, 1995). Recent studies also assess the overall environmental quality of the bay sediments (Anderson, 1994;Fairey et al. , 1996). All of these studies indicate that some common contaminants were found at elevated levels in the sediments. The major sediment chemicals of interest in the NAVSTA area are copper, mercury, zinc, PCBs, and PAHs. Some studies also indicated pesticides may be a problem at localized sites (Fairey et al., 1996). These studies indicated that the areas with the highest chemical concentrations included the commercial shipyards north of NAVSTA and Paleta Creek within NAVSTA. Elevated chemical levels in sediments may represent historic loadings since sediments tend to act as sinks for chemicals in the overlying water and retain them over time. Previous studies indicated that strong gradients in sediment chemical properties would be found along the east–west gradient defined by stations NSB1 through NSB-6, and that these stations would span the observed physical and chemical properties of NAVSTA sediments (Anderson, 1994).

5.1.1 Methods

The six station locations selected for detailed characterization are situated along two east–west transects in the NAVSTA area, one running halfway across the bay near Pier 4 and the other spanning the width of the bay near Paleta Creek (figure 1). These transect positions were selected based on previous studies [3] that noted elevated metals concentrations in the sediments surrounding the old graving dock and elevated organic contaminants around Paleta Creek.

The transect along Pier 4 was selected because of its proximity to the graving dock. Stations were selected along the quay wall (Station NSB-3), at the end of Pier 4 (Station NSB-1), and on the west side of the dredged channel (Station NSB-2). The south transect runs out from Paleta Creek and was selected because of previous reports of strong gradients in PAHs in this area. Stations were selected along the quay wall inside Paleta Creek (Station NSB-5), at the end of Pier 8 (Station NSB-4), and across the bay at a Reference Sta-

tion (Station NSB-6). The station numbers represent the chronological order in which the stations were sampled during the summer of 1995.

At these six stations, divers collected multiple sample cores to ensure sediment surfaces were undisturbed. Cores were recovered from a square approximately 40 cm by 40 cm at each station. Cores were returned to SSC San Diego and processed within 2 to 4 hours of collection. The top 10 cm of sediment from multiple cores at each station were homogenized and split for three measurements: (1) bulk solid chemistry, (2) pore water chemistry, and (3) acid volatile sulfide (AVS) and simultaneously extracted metals (SEM). AVS is operationally defined as the fraction of sulfide present in the sediment that is extracted with cold hydrochloric acid and SEM is the amount of simultaneously extracted metal that is recovered during the AVS determination. The ratio of SEM to AVS gives an indication of how bioavailable trace metals in the sediment are to pore water and sediment dwelling organisms.

Total organic carbon (TOC) and grain-size measurements were made because they tend to bind with any existing contaminants. TOC measurements were made on an automated carbon analyzer by measuring total carbon and inorganic carbon contents, with the difference providing the TOC values. Grain size measurements were made by combination of sieving and hydrometer analysis following accepted American Society for Testing and Materials (ASTM) standard procedures.

Chemical analysis for metals and organics was done directly. Figure 8 outlines the procedure for metals determination. Figure 9 outlines the procedure for organics determination. All samples were sent overnight at approximately 4°C to Battelle's Marine Science Laboratory in Washington for measurement following procedures described by National Oceanic and Atmospheric Administration (NOAA) National Status and Trends (NS&T) analytical protocols (Crecelius et al., 1993). AVS and SEM measurements were made following procedures given in Allen et al. (1993). Samples were collected at Stations NSB-R2-1 through NSB-R2-48 (see figure 1) during 1997 by Van-veen grab. Subsequent processing and analysis was similar to that described for the cores at Stations NSB-1 through NSB-6 except analysis was limited to grain size, TOC, metals, PAHs, PCBs and pesticides.

5.1.2 Analysis Results

Table 3 provides sediment grain size and TOC data for the six stations in this study. At the six stations, TOC ranged from 0.78 to 2.4 percent and, except at Station NSB-2, the sediment textures were very similar with regard to grain size composition. This study showed values of TOC between 1.6 to 2.4 percent around the piers, with the highest value near the quay wall between Piers 4 and 5. Data in the SSC San Diego database taken within the last 10 years also indicate that high TOC values (some above 5 percent) have been reported along the quay wall at NAVSTA and in the commercial shipyards to the north of NAVSTA. Sites around NAVSTA generally have finer grain size and higher TOC values than sites to the west outside NAVSTA boundaries, which may be due to the deep water and reduced tidal currents around the piers that allow fine grained material to settle out of the water column (figure 10). These conditions in the NAVSTA region contribute to the deposition and retention of chemicals from sources around the bay because of their tendency to bind with these fine-grained, TOC-rich sediments.

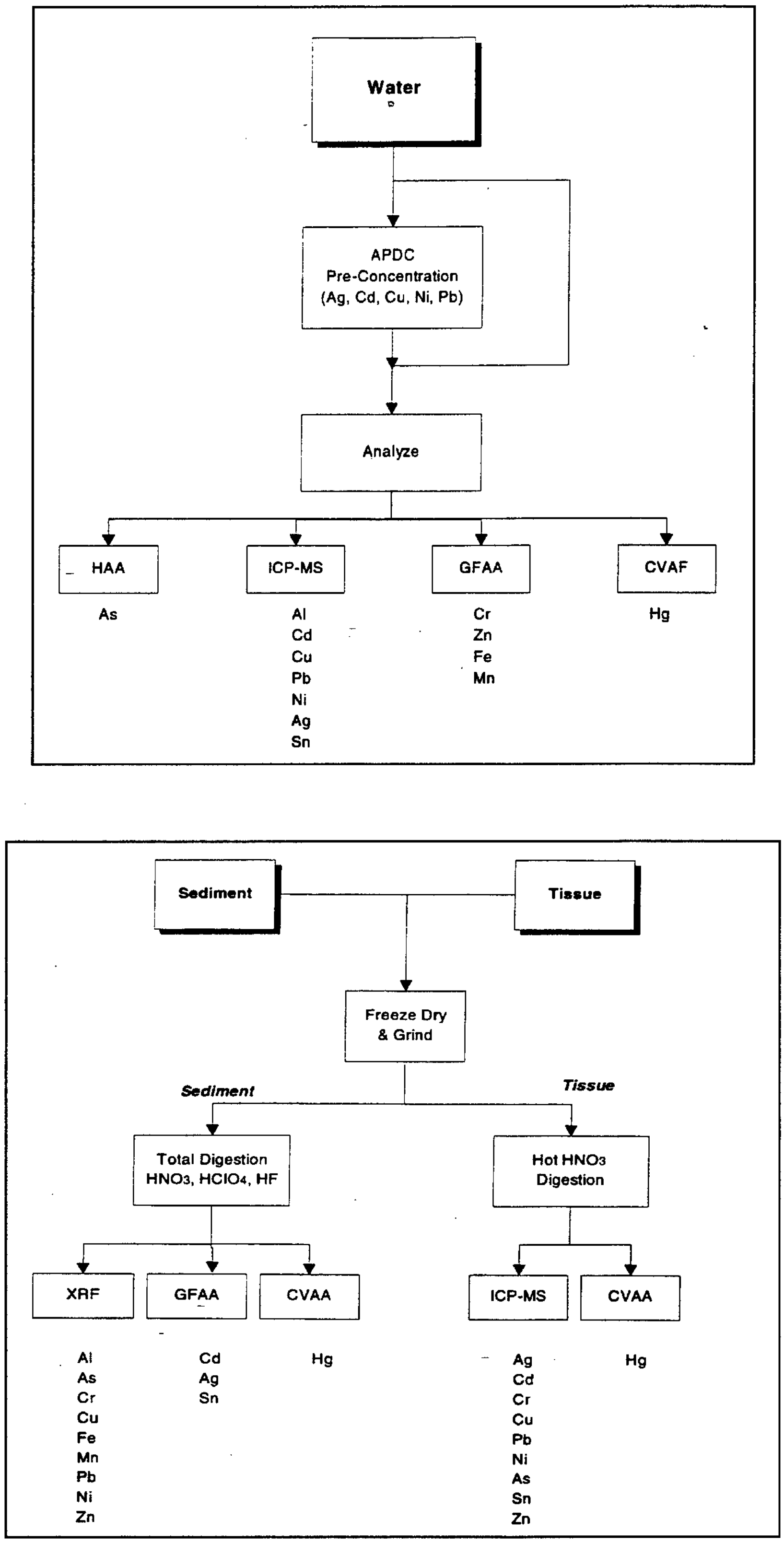

Figure 8. Analysis flowcharts for metal concentrations in water and sediment.

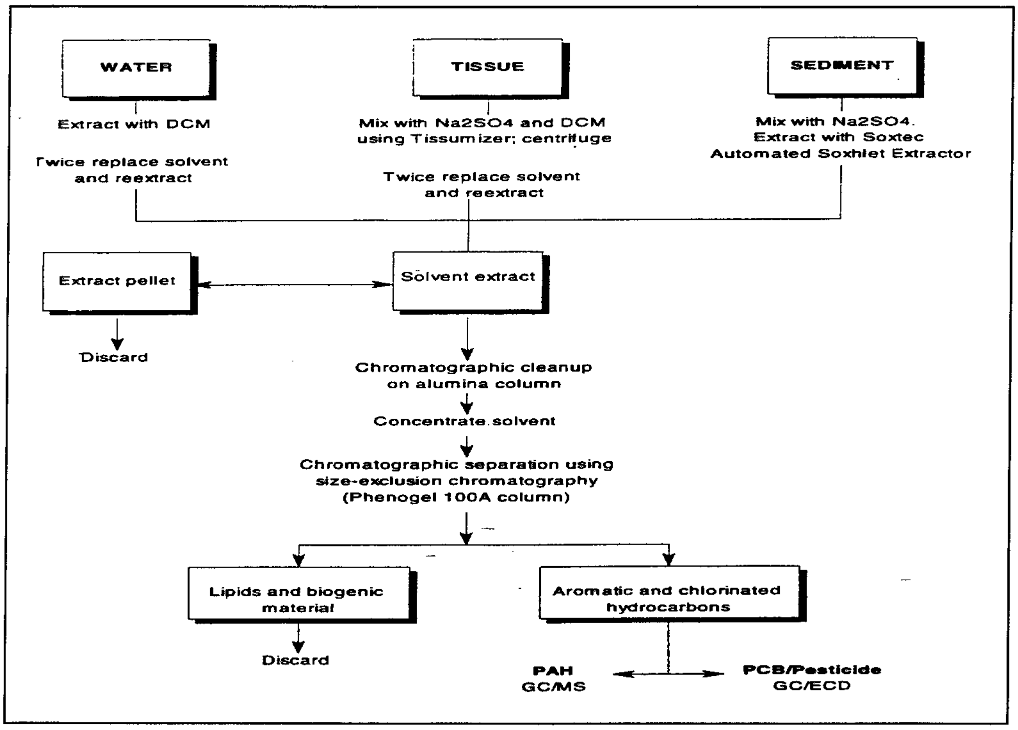

Figure 9. Analysis flowchart for organic chemicals.

Table 4 provides the sediment trace metals measured in this study. Station NSB-1 had three field samples measured, Station NSB-3 had two field samples measured, and all other stations had one sample measured. Stations NSB-5 and NSB-6 had some laboratory replicates measured to gauge laboratory reproducibility on the same sample matrix. The standard deviations for the various metals from the three field samples at Station NSB-1 are small relative to the differences between stations, indicating that differences between stations are significant. In general, it is assumed these standard deviations are representative of the other stations as well, although an obvious exception is Station NSB-3 where high metal levels appear more heterogeneously distributed for some metals such as cadmium and nickel. The overall pattern, however, appears to be higher metals content at sites around NAVSTA piers compared to sites to the west. This pattern is similar to that noted for grain size and TOC in the above discussion, which demonstrates the importance of these binding phases in controlling the distribution of metals in these sediments.

To put these data in perspective, it is useful to compare this study's data with other sediment measurements. NOAA has a long-term monitoring program to assess the environmental condition of sediments across the USA, called the NS&T program. The NOAA NS&T west coast data were filtered to remove sites from inside bays, estuaries, and other industrial areas to provide background data for comparison that represents natural conditions as closely as possible. This way, any areas that may be impacted by anthropogenic activity, resulting in higher background levels than naturally occurring, are removed. Without separating NAVSTA and non-NAVSTA inputs at this point, this method allows an overall comparison of chemical levels in regions specific to this study to assumed "clean" regions. Thus, this approach should be considered a comparison to background conditions and not a comparison to bay reference stations.

Table 3. Total organic carbon and grain size in bulk sediments at the six stations sampled in 1995.

Station Number	Rep	Location	% TOC	% Gravel >2.0 mm	% Sand 2.0 to 0.063 mm	% Silt 0.063 to 0.004 mm	% Clay <0.004 mm
NSB-1		End of Pier 4	1.6	2	49	24	25
NSB-1R		End of Pier 4	1.9	13	42	20	25
NSB-1R		End of Pier 4	1.9	2	43	23	32
NSB-2		West Channel Ref.	0.87	3	80	5	12
NSB-3		Quay Wall near Pier 4	2.4	12	39	26	23
NSB-3		Quay Wall near Pier 4	2.2	17	33	24	26
NSB-4	1	End of Pier 8	1.6	0	37	27	36
NSB-4	2	End of Pier 8	NA	1	37	29	33
NSB-5	1	Quay Wall Paleta	1.7	0	46	29	25
NSB-5	2	Quay Wall Paleta	1.7	NA	NA	NA	NA
NSB-6		Ref. South of EOD	0.78	0	51	23	26

Note: Rep indicates replicates that were analyzed using the same sample. When no replicate is designated, the samples were taken separately. NA indicates that data are not available or applicable.

Table 4. Total metals content in bulk sediment at the six stations sampled in 1995. Method blanks were run to determine concentrations resulting from the method without a sample; these results were subtracted out of sample runs (concentrations in $\mu g \cdot g^{-1}$ dry wt except Fe %).

Station #	Rep	Ag	As	Cd	Cr	Cu	Fe %	Hg	Mn	Ni	Pb	Zn
NSB-1		1.89	11.9	0.69	92.2	220	4.17	1.29	399	23.2	97.9	386
NSB-1R		1.65	20.0	0.74	93.8	214	4.46	1.04	450	23.9	122	564
NSB-1R		1.60	18.8	0.97	98.3	314	4.54	1.18	418	23.0	170	499
NSB-2		0.62	7.50	0.20	57.1	83.4	2.94	0.482	365	11.0	38.3	161
NSB-3		3.15	22.7	9.20	122	485	5.36	1.41	420	29.5	153	641
NSB-3		2.93	29.9	1.33	101	521	4.54	1.32	425	57.5	154	680
NSB-4		1.07	13.1	0.40	75.3	180	4.68	0.516	438	22.4	56.7	280
NSB-5	1	0.88	8.70	1.36	75.5	159	4.32	0.596	515	17.8	120	404
NSB-5	2	NA	11.6	NA	77.3	159	4.40	NA	538	26.1	113	398
NSB-6	1	0.87	8.90	0.17	65.7	75.7	3.91	0.469	437	15.9	41.6	189
NSB-6	2	0.85	NA	0.17	NA	NA	NA	0.452	NA	NA	NA	NA
NSB-1 Std. Dev.		0.16	4.4	0.15	3.2	56	0.19	0.13	26	0.5	36.7	90.1
Blank		0.019	NA	0.009	NA	NA	NA	0.012	NA	NA	NA	NA
Detect		0.012	2	0.009	50	5	0	0.002	25	6	5	3

Note: Rep indicates replicates that were analyzed using the same sample. When no replicate is designated, the samples were taken separately. NA indicates that data are not available or applicable. Detect is the detection limit of the analysis, and NSB-1 Std. Dev. indicates the standard deviation of the three samples collected at Station NSB-1.

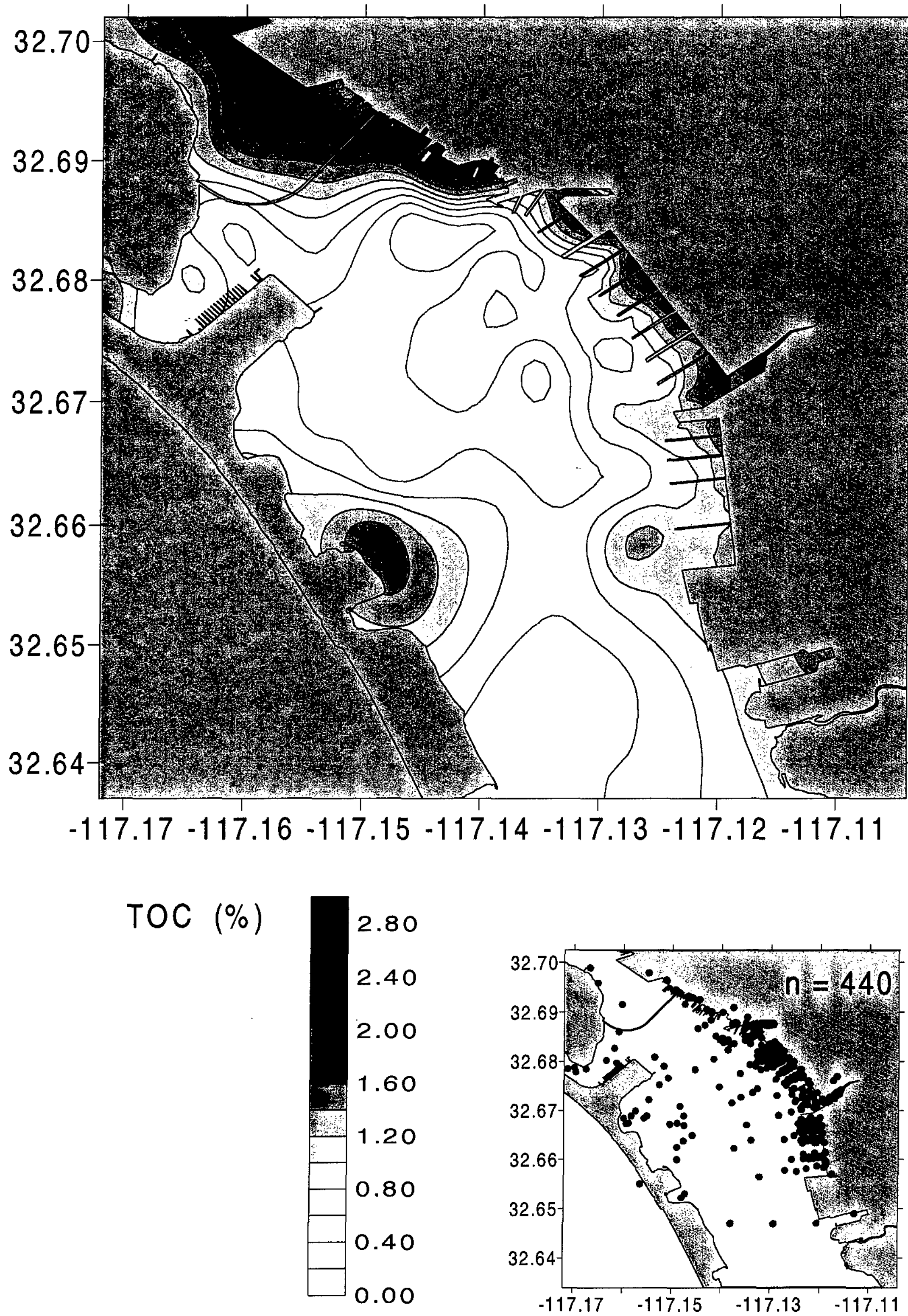

Figure 10. Contour map of the TOC distribution in NAVSTA area sediments. n indicates the number of samples taken.

NOAA has also compiled studies to develop benchmarks that describe certain sediment chemical levels that are likely to result in some adverse biological effects (Long et al., 1995). A lower benchmark, termed the Effects Range Low (ERL), is the chemical level below which less than 10 percent of the compiled studies show adverse effects. An upper benchmark, termed the Effects Range Median (ERM), is the level above which more than 50 percent of the compiled studies show adverse effects.

ERL and ERM levels can be used as one method for screening measured samples to determine the likelihood of ecological effects. Our study data were compiled with data from the SSC San Diego database and compared to NOAA background, ERL, and ERM levels to group the measured metals into three categories: (1) metals of concern, (2) metals of possible concern, and (3) metals not of concern. Individual metals were labeled "metals of concern" if there were multiple stations in the NAVSTA area with sediment levels above the ERM and coastal background level when normalized to iron. Normalizing to iron is done because metals covarying with iron tend to be naturally occurring, whereas those above the iron trend line are usually from some additional source. "Metals of possible concern" were chosen if there were a few stations with levels near the ERM and background. "Metals not of concern" were determined to be those below ERM and generally at or below ERL levels and background. This method was chosen to reach an initial assessment of chemicals of concern. The approach should be considered conservative because comparison to actual reference stations within the bay is likely to reduce the number of sites and chemicals of concern.

When the nine trace metals typically found as contaminants in coastal areas (Long et al., 1995) are grouped as described above, the metals of concern are zinc, copper, and mercury because they are often present in NAVSTA area sediments above ERM levels. Figure 11 shows an example of copper as a function of iron in which copper measurements are both above the ERM and above the upper range of the coastal background. Of possible concern are lead, silver, and cadmium because they are occasionally found near or above ERM levels. Metals not considered of concern because they are found below ERM levels and usually at or below ERL levels are arsenic, chromium, and nickel (see an example of nickel in figure 12).

Spatial distributions were developed for metal contaminants of concern. The spatial maps were produced by grid interpolation of metal concentrations from all available data. From the spatial maps, it is possible to evaluate where chemicals tend to deposit within the NAVSTA region. Figure 13 shows an example for the case of copper. Maps for zinc, lead, mercury, cadmium, and silver show similar distributions. For copper, areas where concentrations exceed the ERM are primarily along the quay wall, at the entrance to Paleta Creek, and along the shoreline to the north of NAVSTA. Some high levels were also observed near the old PACO ore terminal. Concentrations in the mid-bay are generally low, but increase slightly along the western shore (Silver Strand). In general, all of the maps display patterns that are also very similar to the contour maps of TOC and grain size. It is important to stress this general tendency for chemicals to associate with fine particulate material and with higher TOC, since chemicals from many sources around the bay may have contributed to the accumulation of chemicals in these areas.

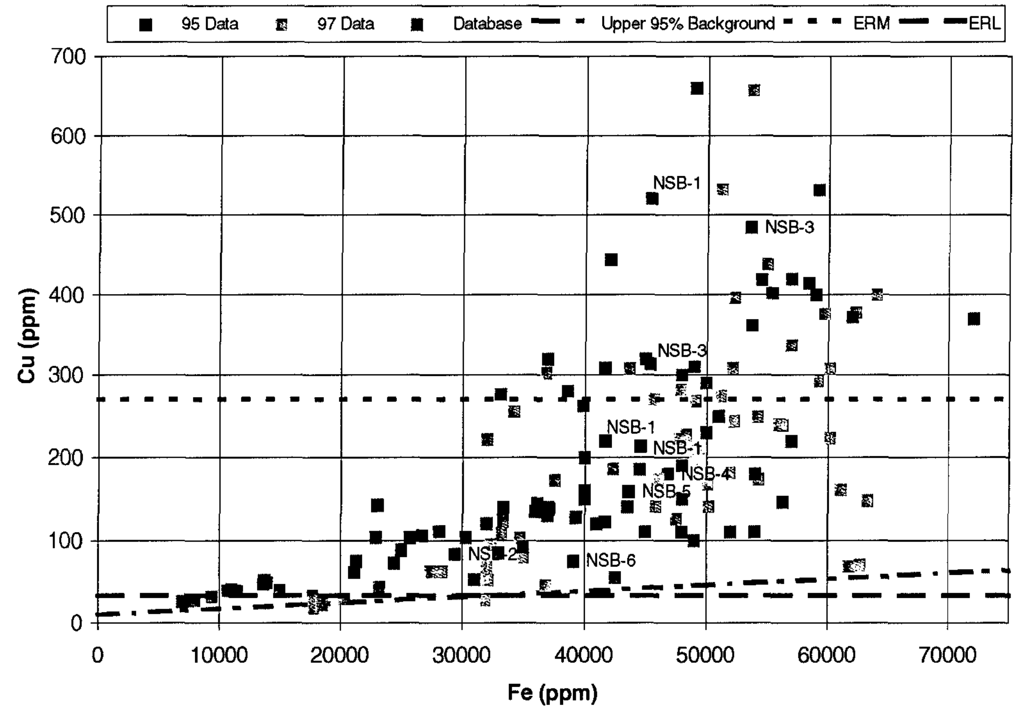

Figure 11. Copper concentrations in sediments as a function of iron content. Most values lie above the upper range of the coastal background, and between the ERL and ERM. Several stations had concentrations above the ERM. On this basis, copper is considered a chemical of concern in the region.

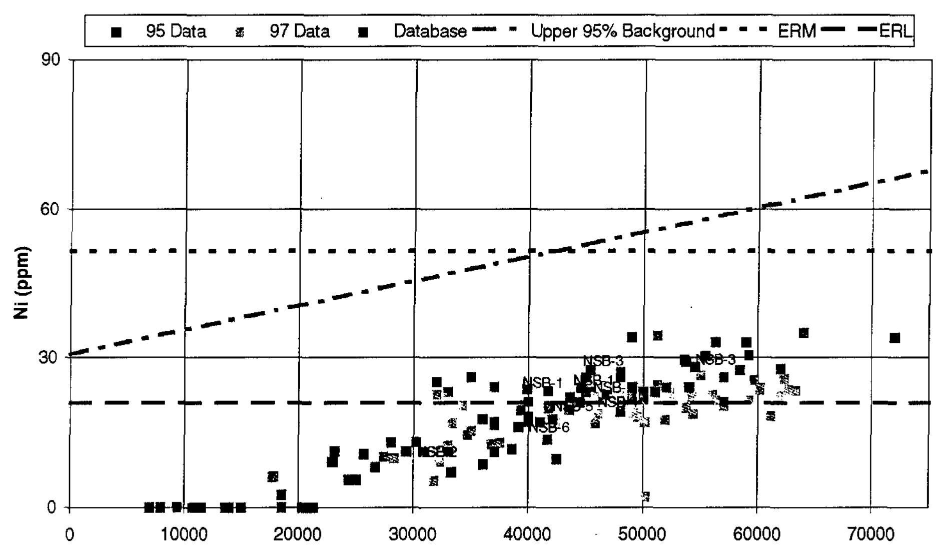

Figure 12. Nickel concentrations in sediments as a function of iron content. All values lie below the upper range of the coastal background, and well below the ERM. Many stations had concentrations below the ERL. Nickel is not considered a chemical of concern.

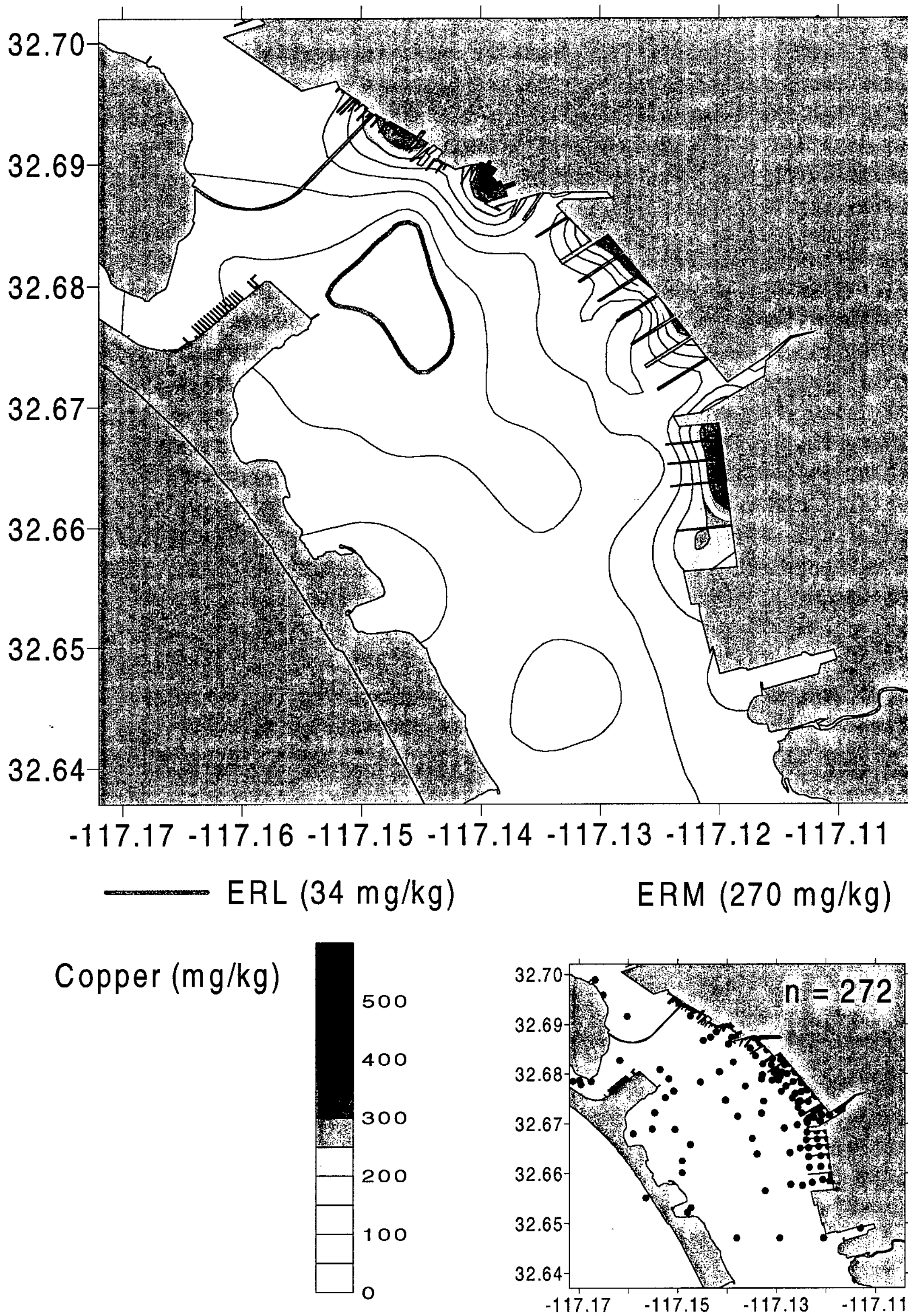

Figure 13. Contour map of copper in NAVSTA area sediments. n indicates the number of samples taken.

To gain information on the amount of sediment trace metals that are bioavailable, additional measurements were made to determine pore water metal, AVS, and SEM levels. AVS is operationally defined as the fraction of sulfide present in the sediment that is extracted with cold hydrochloric acid and SEM is the amount of simultaneously extracted metal that is recovered during the AVS determination. If the amount of AVS is sufficient to totally bind the available SEM in the sediment, metals should not be freely available to the pore water and sediment dwelling organisms.

Benthic toxicity, therefore, may not be directly related to bulk contaminant sediment levels, but rather to the contaminant levels that are bioavailable in the pore water (DiToro et al., 1990). DiToro et al. (1990) have shown that when the molar ratio SEM/AVS is less than 1.0 (SEM<AVS), contaminants in the sediments are not bioavailable and, therefore, not harmful to organisms. When the molar ratio SEM/AVS is greater than 1.0 (SEM>AVS), contaminants in the sediments may cause detrimental effects depending on the existence of additional binding phases that serve to reduce bioavailability. Table 5 contains the AVS and SEM data and table 6 contains the pore water metal data for the study stations. All stations show SEM/AVS less than 1.0 except at Station NSB-6. However, Station NSB-6 has both very low AVS and SEM, so any excess SEM is easily bound by additional binding phases such as organic material, inorganic material (e.g., Fe and Mn oxide phases which tend to bind other metals), and other components present at this Reference Station.

Table 5. Site-averaged acid volatile sulfide (AVS) and simultaneously extracted metal (SEM) in bulk sediment ($\mu mole \cdot g \cdot dry^{-1}$). Only the Reference Station NSB-6 had SEM/AVS>1 (shaded).

Station	AVS	Total SEM	SEM/AVS	SEM (Cd)	SEM (Cu)	SEM (Hg)	SEM (Ni)	SEM (Pb)	SEM (Zn)
NSB-1	8.13	7.97	0.98	0.004	1.09	4.90E-05	0.055	0.19	6.63
NSB-2	4.24	2.17	0.51	0.001	0.55	3.22E-05	0.011	0.12	1.49
NSB-3	19.70	9.09	0.46	0.029	1.74	3.94E-05	0.027	0.31	6.98
NSB-4	4.44	3.92	0.88	0.003	1.22	1.11E-04	0.056	0.15	2.49
NSB-5	13.00	4.35	0.33	0.009	0.60	2.32E-05	0.022	0.30	3.43
NSB-6	0.71	1.88	2.64	0.000	0.39	1.78E-04	0.018	0.09	1.38

Another method to evaluate the level of metals in these sediments is to compare pore water metal levels to water quality criteria (EPA, 1997). One way of predicting pore water levels is by using equilibrium partitioning (DiToro et al., 1991); however, this method depends on theoretical calculations and has inherent uncertainty associated with it. To reduce uncertainty, in this study pore water chemical measurements were taken directly (Bufflap and Allen, 1995). Due to the presence of AVS binding in the measured sediments, all pore water metal levels were far below proposed WQC. This is also reflected in the pore water hazard quotient for the worst station (Max HQ = $[C_{metal}]/C_{WQC}]$), which is significantly less than one (the hazard threshold) for all stations and all metals. Since it is the pore water metal levels rather than the bulk sediment levels that contribute to toxicity (DiToro et al., 1990), the low pore water levels suggest limited toxicity from metal exposure.

Table 6. Dissolved metals from pore waters in bulk sediment ($\mu g \cdot L^{-1}$). Proposed WQC for the State of California are shown as well as the pore water hazard index (Max HQ = $[C_{metal}]/C_{WQC}]$). Pore water levels did not exceed WQC for any metal at any station.

Station	Ag	As	Cd	Cr	Cu	Fe	Mn	Ni	Pb	Zn
NSB-1	0.0050	5.38	0.018	0.26	0.43	3135	1600	1.05	0.32	8.85
NSB-2	0.0021	1.27	0.014	0.09	0.26	36	899	0.41	0.15	8.89
NSB-3	0.0010	9.87	0.015	0.46	0.34	5307	928	0.99	0.12	6.42
NSB-4	0.0050	14.70	0.010	0.14	0.52	7610	2180	1.08	0.10	16.40
NSB-5	0.0001	2.82	0.019	0.71	0.41	492	242	0.48	0.26	4.49
NSB-6	0.0050	3.52	0.037	0.10	0.93	3590	743	0.59	0.31	13.90
Prop. CA WQC	1.9	36	9.3	50	3.1	-	-	8.2	8.1	81
Max HQ	0.003	0.41	0.004	0.01	0.30	-	-	0.13	0.04	0.20

Organic chemicals were measured in sediments at Stations NSB-4 through NSB-6 (Paleta Creek Transect), including PAHs and PCBs (tables 7 and 9). PAHs are organic compounds composed of two or more fused benzene rings that are commonly found in petroleum products. They may be introduced to the marine environment directly through petroleum spills and leaching of creosote-treated pilings, or indirectly via atmospheric transport following incomplete combustion of petroleum or organic materials. PCBs are strictly man-made chemicals produced over the past 50 years for various industrial uses related to their thermal stability and non-reactive nature. Although their use is being phased out, PCBs are resistant to breakdown and may ultimately become deposited in the sediments where they persist in the environment for long periods of time. Since most PAHs and all PCBs are introduced through human activities, there are no large naturally occurring background levels as seen in the case of most trace metals.

As with the metals data, the PAH and PCB data were compiled with additional regional data from the SSC San Diego database to provide a broader comparison. Most data for this region fall well below the ERM level. Station NSB-4 with 94 ppm total polycyclic aromatic hydrocarbon (TPAH) and two stations from the 1997 survey appear as outliers and represent a special situation. During the summer of 1995 just prior to field collection at this station at the end of Pier 8, the wooden pilings were replaced with new plastic and untreated pilings under an ongoing NAVSTA program to reduce creosote leaching into the bay. Since most database sites show high values for TPAH around 20 ppm, the value over 94 ppm possibly represents some creosote material deposited in the sediments during this replacement program. It is also a very localized hot spot because on collection trips back to this area we have only been able to re-sample values in the 20 ppm range. Other than these localized hot-spots, the data show a pattern very similar to that seen in the metals plots in that at higher TOC values (corresponding to higher Fe and percent of fine material), TPAH values rise above the ERL up to a high around 20 ppm (figure 14). The stations with TPAH values above ERL, including Station NSB-5, are all in the depositional region on the east side of the bay among the NAVSTA piers and to the north of NAVSTA.

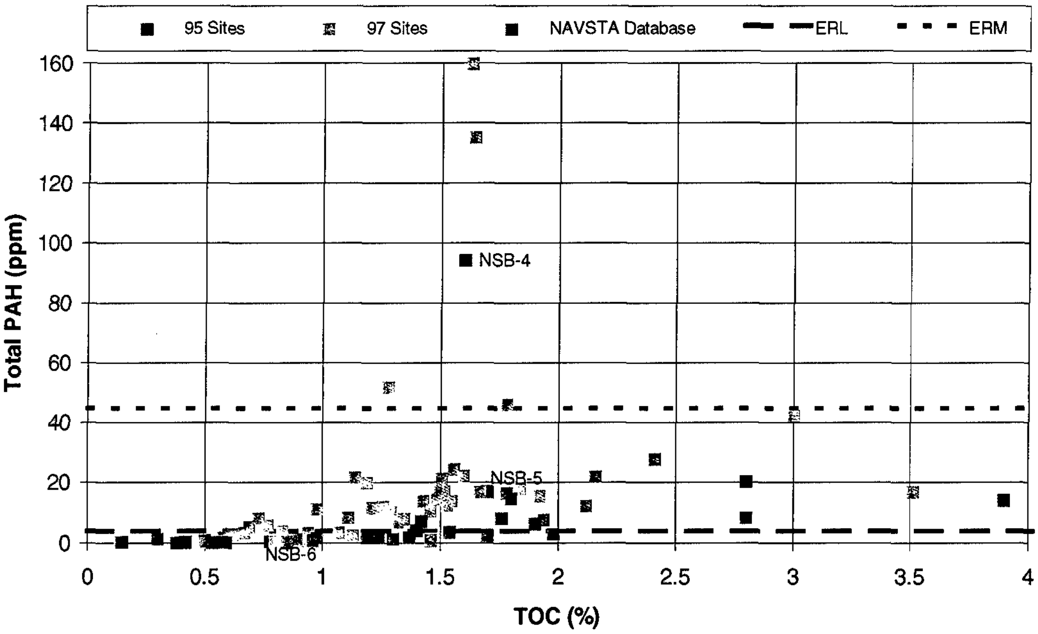

Figure 14. Total PAH concentrations (μg·g^{-1} dry wt) in sediments from the NAVSTA region as a function of TOC (%).

Table 7. Polycyclic aromatic hydrocarbons (PAHs) in bulk sediments (ng·g^{-1} dry wt). Shaded cells in the body of the table indicate values exceeding ERM.

PAHs	NSB-4	NSB-5	NSB-6	NSB-6 (Rep)	ERL	ERM
Naphthalene	28.7	76.0	8.31	7.27	160	2100
Acenaphthylene	608	103	9.38	7.64	44	640
Acenaphthene	607	41.0	2.04	1.43	16	500
Fluorene	1022	70.7	4.75	2.84	19	540
Dibenzothiophene	284	14.5	1.98	1.52	-	-
Phenanthrene	5340	246	21.6	13.3	240	1500
Anthracene	5200	284	9.87	8.91	85.3	1100
Fluoranthene	22300	972	48.2	43.7	600	5100
Pyrene	15500	4130	58.8	57.3	665	2600
Benzo(a)anthracene	6860	526	23.4	20.3	261	1600
Chrysene	11900	1540	36.0	30.6	384	2800
Benzo(b)fluoranthene	8070	2700	73.9	68.9	-	-
Benzo(k)fluoranthene	3080	1020	25.8	24.3	-	-
Benzo(e)pyrene	3510	1370	47.1	45.6	-	-
Benzo(a)pyrene	5050	1540	51.9	50.1	430	1600
Perylene	1400	405	14.7	13.9	-	-
Indeno(123-cd)pyrene	1670	819	47.6	47.1	-	-
Dibenzo(a,h)anthracene	528	235	8.72	8.44	63.4	260
Benzo(g,h,l)perylene	1280	795	54.4	55.3	-	-
Total PAH (sum of above)	94200	16900	548	508	4000	44800

Pyrene and fluoranthene, respectively, are the two most common of the measured PAHs in the sediments. These middleweight-to-heavyweight PAHs are generally most common in the sediments because in PAHs both solubility and volatility decrease with molecular weight. The sediment PAH composition is highly fractionated compared to any source composition, with very few lighter compounds and the bulk of the PAHs in the middleweight-to-heavyweight range. Both pyrene and fluoranthene show similar patterns to total PAHs, but the relative variations in the individual ERMs lead to more stations above the ERM. Since some stations have both total and individual PAHs above the ERM, PAHs are considered a chemical of concern. Total PCBs were calculated as the sum of individual congeners (individual PCB compound) reported in table 9. Several stations from this study and the SSC San Diego database are above the ERM for total PCBs, so PCBs are also considered chemicals of concern in the NAVSTA area.

Organic chemicals in pore waters that were measured included the PCBs and PAHs listed in tables 8 and 10. In a similar fashion to that used for the metals, PAHs and PCBs in the pore water can be compared to WQC to judge relative toxicity. In general, total PAH and total PCBs in the pore waters fall below EPA Acute Saltwater WQC, even at Station NSB-4 where elevated bulk sediment PAHs and PCBs are present. However, some individual PAHs (e.g., fluoranthene) in the pore water at Station NSB-4 do come close to the chronic WQC, and total PCB levels are in the range of the EPA chronic WQC at both the NAVSTA stations and the Reference Station.

Table 8. Polycyclic aromatic hydrocarbons (PAHs) in pore water samples ($\mu g \cdot L^{-1}$).

PAHs	NSB-4	NSB-5	NSB-6	EPA WQC (acute/chronic)
Naphthalene	0.25	0.16	0.18	N/A - None Available
Acenaphthylene	0.66	0.035	0.040	N/A
Acenaphthene	20.6	0.069	0.038	970/710
Fluorene	14.2	0.091	0.11	N/A
Dibenzothiop	4.06	0.043	0.049	N/A
Phenanthrene	28.9	0.21	0.050	N/A
Anthracene	3.33	0.11	0.060	N/A
Fluoranthene	13.1	0.99	0.062	40/16
Pyrene	11.3	0.57	0.086	N/A
Benzo(a)anthracene	1.82	0.21	0.11	N/A
Chrysen	1.20	0.18	0.030	N/A
Benzo(b)fluoranthen	1.19	0.33	0.045	N/A
Benzo(k)fluoranthen	0.46	0.13	0.039	N/A
Benzo(e)pyrene	0.51	0.17	0.023	N/A
Benzo(a)pyrene	0.63	0.20	0.018	N/A
Perylene	0.16	0.058	0.023	N/A
Indeno(123-	0.20	0.081	0.048	N/A
Dibenzo(a,h)anthracene	0.056	0.024	0.019	N/A
Benzo(g,h,i)perylene	0.16	0.083	0.095	N/A
Total PAH (sum of	103	3.74	1.12	300/-

Table 9. Polychlorinated biphenyls (PCBs) in bulk sediments (ng·g^{-1} dry wt). Shaded cells in the body of the table indicate values exceeding ERM.

PCB Congeners	NSB-4	NSB-5	NSB-6	ERL	ERM
PCB 8	1.17	0.45	0.42	-	-
PCB 18	1.15	0.15	0.23	-	-
PCB 28	1.18	0.05	0.31	-	-
PCB 29	0.06	0.05	0.05	-	-
PCB 44	11.6	0.02	1.05	-	-
PCB 49	6.81	0.05	0.68	-	-
PCB 50	0.06	0.05	0.07	-	-
PCB 52	28.4	0.81	2.66	-	-
PCB 66	0.03	0.02	0.02	-	-
PCB 87	21.3	0.41	2.12	-	-
PCB 101	45.1	1.62	5.28	-	-
PCB 104	3.60	0.05	0.05	-	-
PCB 105	15.2	0.85	1.91	-	-
PCB 118	41.8	1.96	5.53	-	-
PCB 128	7.16	0.83	1.39	-	-
PCB 138	30.0	3.27	5.55	-	-
PCB 153	32.2	3.71	6.38	-	-
PCB 154	0.06	0.05	0.05	-	-
PCB 170	8.05	1.52	1.54	-	-
PCB 180	9.68	1.88	2.53	-	-
PCB 183	6.25	0.64	1.09	-	-
PCB 184	0.06	0.09	0.05	-	-
PCB 187	6.76	1.58	2.24	-	-
PCB 188	0.06	0.05	0.05	-	-
PCB 195	0.02	0.02	0.32	-	-
PCB 200	0.06	0.05	0.05	-	-
PCB 206	0.03	0.74	0.65	-	-
PCB 209	0.02	1.36	1.17	-	-
Total PCB (Sum of above)	278	22	43	4.0	180

Table 10. Polychlorinated biphenyls (PCBs) in pore water samples (ng·L^{-1}).

PCB Congeners	NSB-4	NSB-5	NSB-6	EPA WQC
PCB 8	1.69	1.81	2.07	N/A - None Available
PCB 18	1.79	1.91	2.20	N/A
PCB 29	0.94	1.00	1.15	N/A
PCB 50	1.59	1.70	1.95	N/A
PCB 28	8.40	1.28	1.47	N/A
PCB 52	0.60	0.64	0.74	N/A
PCB 49	0.91	1.00	1.11	N/A
PCB 104	0.57	0.61	0.69	N/A
PCB 44	0.52	0.56	0.64	N/A
PCB 66	1.55	0.69	0.79	N/A
PCB 101	0.83	0.88	1.01	N/A
PCB 154	1.74	1.00	1.15	N/A
PCB 87	1.43	1.43	0.74	N/A
PCB 188	0.38	0.40	0.46	N/A
PCB 118	0.80	1.62	0.98	N/A
PCB 184	0.91	0.97	1.11	N/A
PCB 153	0.67	2.32	0.82	N/A
PCB 105	0.50	0.54	0.62	N/A
PCB 138	0.58	1.98	0.71	N/A
PCB 187	0.66	0.70	0.80	N/A
PCB 183	0.91	0.97	1.11	N/A
PCB 126	1.86	1.09	1.25	N/A
PCB 128	0.41	0.44	0.50	N/A
PCB 200	2.42	2.59	2.97	N/A
PCB 180	0.47	0.50	0.57	N/A
PCB 170	0.34	1.88	0.41	N/A
PCB 195	0.46	0.49	0.57	N/A
PCB 206	0.66	0.71	0.81	N/A
PCB 209	0.47	0.50	0.57	N/A
Total PCBs (sum of	35.06	32.21	29.97	10000/30

5.1.3 Summary of Sediment Physical and Chemical Characteristics

Several lines of evidence were evaluated in the chemical characterization studies, including sediment physical/organic properties, bulk chemical loading, metal bioavailability in sediments in the presence of AVS, and metal, PAH, and PCB concentrations in pore water. From a weight-of-evidence perspective, each aspect of the characterization provides a line of evidence by which to evaluate the sediment quality.

The distribution of sediment physical properties indicates that fine, organic-rich sediments are preferentially trapped and deposited in the low-current areas found within the NAVSTA piers. A strong correlation between these sediments with a high capacity to bind chemical compounds and elevated chemical concentrations indicates that the spatial distribution of contaminants is strongly controlled by the physical circulation of the Bay, and is not simply a function of proximity to contaminant sources.

Bulk sediment chemical analysis for metals indicates that zinc, copper, and mercury could be considered potential chemicals of concern in the NAVSTA area because numerous study stations show values above ERM levels. Lead, silver, and cadmium show some study and database sites near or above ERM levels, so they could be considered possible chemicals of concern. Arsenic, chromium, and nickel do not show any stations near the ERM level and are usually at or below ERL levels so, on this basis, they are not major chemicals of concern in the NAVSTA area. However, pore water chemistry indicates that although metal may be present at elevated concentrations in the bulk sediment, concentrations in the pore water are far below water quality criteria (WQC). This result means that metal toxicity due to elevated metal concentrations in pore water is not expected from "in-place" sediments. Further evidence for this limited bioavailability of metals is found in the SEM/AVS ratios that generally fall below one, indicating metals are strongly bound in sulfide complexes and are not bioavailable.

Bulk sediment chemistry for organic chemicals indicates that PAHs and PCBs could both be considered possible chemicals of concern in the NAVSTA area because some study and database sites show values at or above ERM levels. However, as with metals, pore water PAH concentrations were generally below acute and chronic WQC, except for an anomalously high level at Station NSB-4 where phenanthrene approached the chronic WQC. Pore water PCB concentrations were in all cases below the acute WQC but for both the NAVSTA stations and the Reference Station, levels were in the same range as the chronic WQC.

5.2 BIOASSAY AND BENTHIC COMMUNITY STUDIES

The purpose of this section is to describe bioassay studies performed in San Diego Bay, with emphasis placed on the NAVSTA area. Some effort is also given to potential associations of effects noted and likely source inputs.

The principle focus of bioassay work performed in the Bay has been associated with dredging and the required studies necessary to characterize dredged sediment for appropriate disposal. In these cases, the areas to be dredged have defined where, and which, bioassays were performed, and the extent of aerial coverage studied. Other studies have attempted to identify contaminated sediments spatially as well. These studies have not been concerned with dredged sediment toxicity solely. Collectively, these various studies have provided sediment toxicity data including various areas in the Bay as well as various sediment depths;

specifically, areas bordering NAVSTA, multiple species bioassay data, and historical sediment pollution. Because differing objectives have guided sampling designs, some gaps exist in the data, specifically in aerial coverage. With respect to NAVSTA, data are scarce near the quay wall area and away from the piers toward the center of the bay. This scarcity of data complicates analysis of pollutant impact from runoff and other sources in the NAVSTA region.

5.2.1 Listing of Recent Bioassay and Benthic Community Studies

Several recent studies dealing with bioassay and benthic communities relevant to NAVSTA sediments and proposed or completed dredging projects are listed below.

Bioassay Studies

- Sediment Characterization Report for Chollas Creek, Naval Station San Diego [10]
- Dredged Material Bioassay Testing Program, MCON Project M10-90, Maintenance Dredging Naval Station San Diego [11]
- Dredged Material Bioassay Testing Program Results MCON Project P-338S Pier 3 Dredging Naval Station San Diego CA [12]
- Dredged Material Bioassay Testing Program Results M10-90 Maintenance Dredging Pier 8 and Mole Pier Naval Station San Diego CA [13]
- Sediment Characterization Study Pier and Berthing Areas U.S. Naval Station San Diego Final Report [14]
- Results of Dredge Bioassay on Sediments from Pier 3, 32nd Street Naval Base in the Port of San Diego [15]
- Assessment of Pier 2 Approach Dredged Material for Beach Replenishment Naval Station San Diego [16]
- Chemistry, Toxicity and Benthic Community Conditions in Sediments of the San Diego Bay Region—Final Report [17]
- Studies Supporting an Environmental Risk Assessment of San Diego Bay, Final Report - Final Report (Anderson, 1994)

Benthic Community Studies

- Marine Sampling and Analysis in Support of Task A, Environmental Impact Statement, Naval Station San Diego [6]
- Chemistry, Toxicity and Benthic Community Conditions in Sediments of the San Diego Bay Region - Final Report [17]

5.2.2 Current Bioassay Studies

The majority of previous bioassay measurements in the NAVSTA region were performed on whole sediments. These tests provide a measure of the potential effects of in-place sedi-

ments on a variety of benthic organisms. Given the relatively large database of existing whole sediment bioassay results, it was decided that the focus of this study should be restricted to suspended-phase and pore water testing. The importance of this approach is due to the large number of ship movements and consequent resuspension events that occur in the NAVSTA region described in section 6.3.2 (Sediment Resuspension by Ships). The suspended-phase (elutriate) testing performed provides a direct measure of the potential effects of these resuspension events on a range of marine organisms. In conjunction with suspended-phase leachate chemical analysis, these results provide the means to quantify this potentially important mechanism of contaminant exposure. Because the tests are standard sediment assays, they are also useful for interpreting potential effects of in-place sediment.

Methods. A series of static-renewal EPA bioassays, in addition to a suite of Microtox and QwikSed bioluminescence bioassay tests, were conducted to estimate the potential effects of marine sediments collected at six stations adjacent to NAVSTA. The sediments were tested on the mysid shrimp (*Mysidopsis bahia*), the inland silversides (*Menidia beryllina*), the bioluminescent dinoflagellate (*Gonyaulax polyhedra*), the bioluminescent bacteria (*Photobacterium phosphoreum*), and the marine chain diatom (*Skeletonema costatum*, clone "Skel"). The marine diatom was used for the chlorophyll assays. Bioassay organisms representing different phyla were chosen and tested to represent a potential "risk" to the marine environment. *Mysidopsis bahia* was chosen to represent a benthic or bottom-dwelling animal response, while *Menidia beryllina* was chosen to represent a pelagic or swimming animal response. The phytoplankton chain diatom species and the dinoflagellate were used to observe any potential effect on the primary producers in marine waters. The endpoints measured were the concentration at which 50 percent of test organisms were affected (LC_{50} or IC_{50}) and the concentration at which no observable effect occurred (the No Observable Effect Concentration or NOEC). LC_{50} is the lethal concentration at which 50 percent of the organisms do not survive, and IC_{50} is the inhibition concentration at which 50 percent of the organisms are inhibited in some manner such as reduction in light emitted or loss of mobility, among others. The endpoints were survival in the mysids and fish (LC_{50}), inhibition of bioluminescence of *G. polyhedra* and the bacterium (IC_{50}), and biomass or chlorophyll fluorescence (IC_{50}) in the diatom tests.

Both sediment leachates and pore waters were tested; however, the preparation methods used were different. Sediment test solutions were attained by leaching each sediment in filtered sea water for 1.5 hours, in which 30 min of mixing was followed by 1 hour of settling period (USEPA/USACE, 1991). A 25 percent elutriate was prepared (USEPA/USACE, 1991) by sub-sampling 1 L of filtered sea water exposed to 250 grams of mixed sediment (1:4 ratio). This 25 percent elutriate was then used as 100 percent test solution. For testing purposes and to determine a dose-response curve, the 100 percent test solution was diluted with filtered sea water by half until reaching 6.25 percent. In the case of the pore water, the samples were not mixed with sea water originally to obtain the 100 percent solution, but were diluted for testing purposes and to determine a dose-response curve by diluting by half until reaching 6.25 percent.

Results. Sediment elutriates produced an LC_{50} at Stations NSB-2, NSB-4, and NSB-5 with mysid shrimp, while only Station NSB-2 elutriates produced an LC_{50} in inland silversides. Effects were also observed in the diatom at Stations NSB-2, NSB-4, and NSB-5. None of the station sediments produced an IC_{50} in the bacteria *Photobacterium phosphoreum* (Microtox),

while $IC_{50's}$ were observed in the dinoflagellate *Gonyaulax polyhedra* (QwikSed) at all six stations. Figures 15 through 17 are shown as examples of bioassay tests that gave varying results. Figure 15 presents the results of a 96-hour acute bioassay using *Mysidopsis bahia* in which no LC_{50} was observed (at Station NSB-3). Even though control survival was below 90 percent, the fact that toxicity was not observed at stations with the highest metals (e.g., Station NSB-3) may indicate that the bioavailable fraction is below the toxic level. Figure 16 presents results from another 96-hour acute bioassay using *Mysidopsis bahia* in which a LC_{50} was observed at a 61.5 percent elutriate concentration (at Station NSB-5). Figure 17 presents the results of a copper sulfate reference control conducted along with the sediment assays which has levels within acceptable EPA published limits. This was the case for Stations NSB-1 through NSB-4, whereas Stations NSB-5 and NSB-6 were marginally high. Table 11 provides a summary of LC_{50} and IC_{50}'s detected from sediment elutriates.

Discussion. Sediment elutriate test results indicate that only sediments from Stations NSB-2, NSB-4, and NSB-5 would produce effects due to leaching of contaminants, with the exception of the QwikLite test. However, the fact that effects were not observed at stations with the highest metals (e.g., Station NSB-3) may indicate that the bioavailable fraction as discussed in previous sections is below the toxic level. Additionally, the presence of naturally occurring ammonia in sediment elutriates suggest that it may be a contributing factor in observed effects in QwikLite rather than metals.

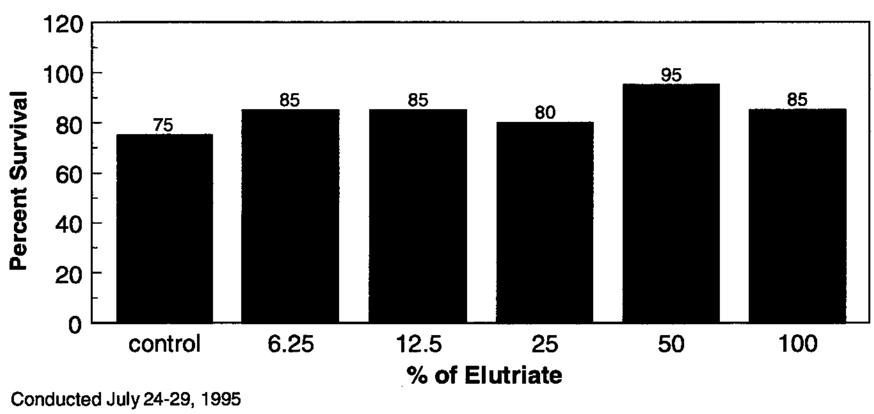

Figure 15. Sediment: NAVSTA Station NSB-3. *Mysidopsis bahia* 96-hour acute bioassay results. LC_{50} was greater than 100 percent elutriate.

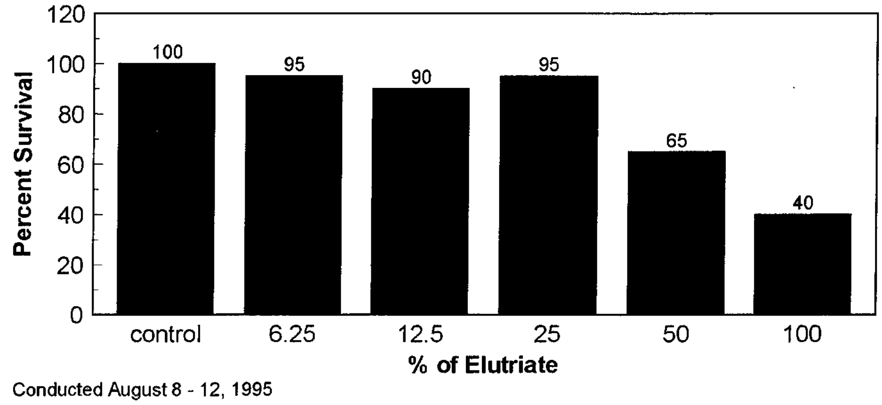

Figure 16. Sediment: NAVSTA Station NSB-5. *Mysidopsis bahia* 96-hour acute bioassay results. LC_{50} was at 61.50 percent elutriate.

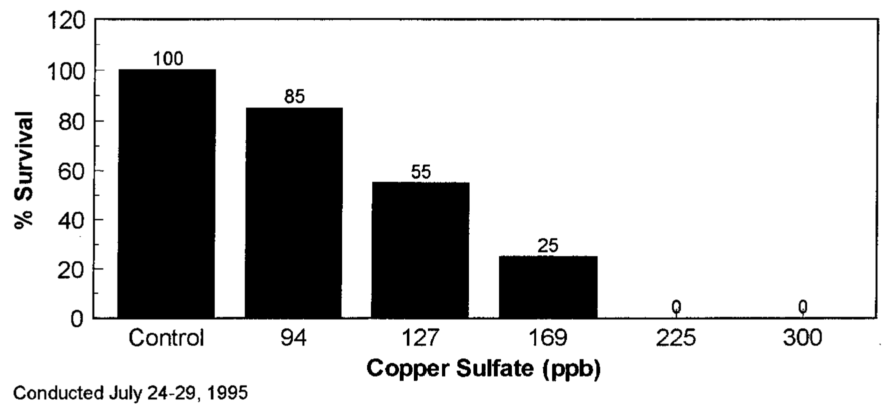

Figure 17. Copper sulfate reference toxicant test conducted with sediment Stations NSB-3 and NSB-4 bioassays with *Mysidopsis bahia*. LC_{50} was at 149 ppb $CuSO_4$.

Table 11. Summary of bioassay results from sediment elutriate studies reported as percent elutriate, causing an LC_{50} or an IC_{50} for various test organisms.

Station	Shrimp (*Mysidopsis*) Elutriate	Minnow (*Menidia*) Elutriate	Diatom (*Skeleto-nema*) Elutriate	Microtox Elutriate	QwikLite (*Gony-aulax*) Elutriate	QwikSed (*Gonyaulax*) Pore Water
NSB-1	*	*	*	*	6.1%	*
NSB-2	61.5%	95.5%	96.4%	*	3.8%	*
NSB-3	*	*	*	*	30.2%	*
NSB-4	41.3%	*	39.3%	*	6.0%	*
NSB-5	61.5%	*	43.5%	*	6.4%	**
NSB-6	*	*	*	*	31.0%	**

*Note: * indicates that the LC_{50} or IC_{50} was greater than the 100 percent elutriate and effects were not observed.*

*** indicates that some effects were observed at 50 percent concentration and no IC_{50} was generated.*

A primary motivation for evaluating elutriate toxicity was to determine if exposure that occurs during resuspension events could lead to effects in Bay organisms. It is possible that this type of exposure could occur either as the result of sediment resuspension events (primarily due to ship movements or during dredging operations) or directly from benthic fluxes. Of the chemicals of concern identified in NAVSTA sediments, zinc showed the strongest tendency for remobilization from benthic fluxes, while cadmium, copper, nickel, lead, and zinc all exhibited remobilization during resuspension experiments. Bioavailability of these chemicals may be strongly controlled by sulfide binding in anoxic sediments. Thus, toxicity induced by metals in the sediments is more likely to occur under aerobic conditions such as occur at the sediment water interface, or during sediment resuspension.

To put the laboratory exposures in perspective, the results must be compared to expected exposure levels in the field. While the exposures in the laboratory experiments were performed with a 25 percent elutriate (250000 $mg \cdot L^{-1}$), the average increase in suspended load observed during the field resuspension studies was 3.3 $mg \cdot L^{-1}$, and the maximum concentration was about 37 $mg \cdot L^{-1}$ (see section 6.3). Thus, in the field, we can expect that exposure levels would be reduced by about a factor of 6700. This indicates that acute toxicity due to exposure during resuspension events is unlikely. This is consistent with the observations in section 6.3 that indicate only minor increases in water column metals concentrations during resuspension events.

No effects were observed from four of the six stations using pore water analysis (table 11), and for the other two stations, the toxicity was not sufficient to generate an IC_{50}. The lower response observed in the pore water indicates active binding of chemicals observed under the reducing conditions present in the sediments around NAVSTA. It may also reflect differences in sample collection, since the pore water samples were collected from the top 2 cm and the elutriate samples from the top 10 cm. It is important to note that ammonia levels were markedly less at the shallower depth than from deeper sediments and this could also explain the lack of toxicity in QwikSed. Effects have been observed in *Gonyaulax polyhedra* in elutriate solutions as low as 1 ppm total ammonia. Previous ammonia levels at Stations NSB-1 through NSB-6 ranged from 2.49 to 7.46 ppm (sediment elutriates). Stations NSB-2, NSB-4, and NSB-5 had the highest levels of ammonia, ranging from 6.64 to 7.46 ppm (total ammonia). Mortality in the bioassays was high at these three stations. Upon re-sampling, ammonia levels were markedly less and ranged from 1.1 to 2.2 ppm (pore waters). QwikLite bioluminescence tested pore waters up through a 50 percent dilution and found no or very little toxicity at five of the six stations tested. The effects of ammonia on QwikLite toxicity have been described in several reports (Lapota et al., 1997; Liu et al., 1998).

Sulfides also reside at deeper depths in the sediments and could be toxic to various bioassay organisms; however, tests have not been conducted to determine any effect. PAHs should still be considered as a possible agent for the effects measured at Station NSB-5 as higher levels of PAHs were observed in Station NSB-5 pore waters.

5.2.3 Sediment Profiling Image Study

Results from previous studies of benthic community health were supplemented using Sediment Profile Imaging (SPI) technology (Arthur D. Little, Inc., 1996). The SPI system allows for rapid characterization of physical and biological indices of sediment quality through the acquisition and analysis of vertical-profile photographic images. EVS Environ-

ment Consultants analyzed and interpreted color slides that were taken in San Diego Harbor in July 1995 using the SPI system. EVS analyzed and interpreted 43 stations. Final selection of stations to be included in the analysis was made by Drs. J. Leather and D. B. Chadwick of SSC San Diego based on relevance to this study. Details of field operations, station locations, and sampling procedures for initial data collection are reported in ADL Reference No. 51858 (Arthur D. Little, Inc., 1996). Representative slides were selected for analysis from Stations A1 through A4, B1 through B6, C1 through C4, C6, C7, D1 through D5, E1 through E4, E6, E7, F2, F4, G1 through G3, H1, H2, I1 through I3, J1, and NSB1 through 6. Slide selection was based on photo quality, image depth, and spatial location relative to NAVSTA. Station locations are shown in figure 18. Color slides were scanned and stored in photo-CD format by ProLab, Inc., Seattle, WA.

The results from this demonstration SPI technology survey reveal that the sediment quality and benthic habitat in the NAVSTA region of San Diego Bay were within what would be considered the normal range, given the water depth, amount of vessel traffic, and range of activities associated with operation of a naval station. Several of the images indicated the presence of sandblasting grit in the upper surface layers. In addition, some of the stations in water depths within the photic zone showed high densities of eelgrass.

Compared with SPI surveys done in other urban harbor areas in similar water depths (Boston, San Francisco, New Haven, and Baltimore), the majority of images from the vicinity of NAVSTA indicated relatively high habitat quality and showed little evidence of adverse impact or potential contaminant "hot-spots," as reflected in benthic community structure and sediment texture. The images from Station B4, which is located in one of the navigational channels, show benthic conditions considered pristine for a relatively healthy shallow-water inner harbor. Only five of the locations analyzed showed any signs of serious adverse impacts. Based on a relationship between degraded habitat quality from the sediment profile images in this survey and potential presence of contaminants, some may be present at concentrations that could cause adverse biological effects near Pier 4 at Stations A1, B2, C1, D1, and NSB-5. Figure 19 demonstrates the range of contrast in sediment quality found within the Bay.

The main source of impacts to the area surveyed seems to be the outflow from the Chollas and Paleta Creeks, as reflected in the distribution of the apparent mean redox potential discontinuity (RPD) depths. The RPD is the depth at which there is an abrupt change in the coloration of the sediment generally associated with the transition from oxygen or metal reduction to sulfide reduction. The depth of this boundary tends to vary depending on the organic loading to the sediment, and the disturbance of the sediment due to biological activity. Evidence of past depositional events (most likely during periods of high water flow) can be seen at locations near the creek mouths in the sand-mud-sand stratigraphy in the upper surface layers. In addition, stations with the highest organic loading (consequently highest sediment oxygen demand (SOD)) and poorest sediment quality for benthic infauna are located nearest the creek mouths (Stations A1, C1, and NSB-5).

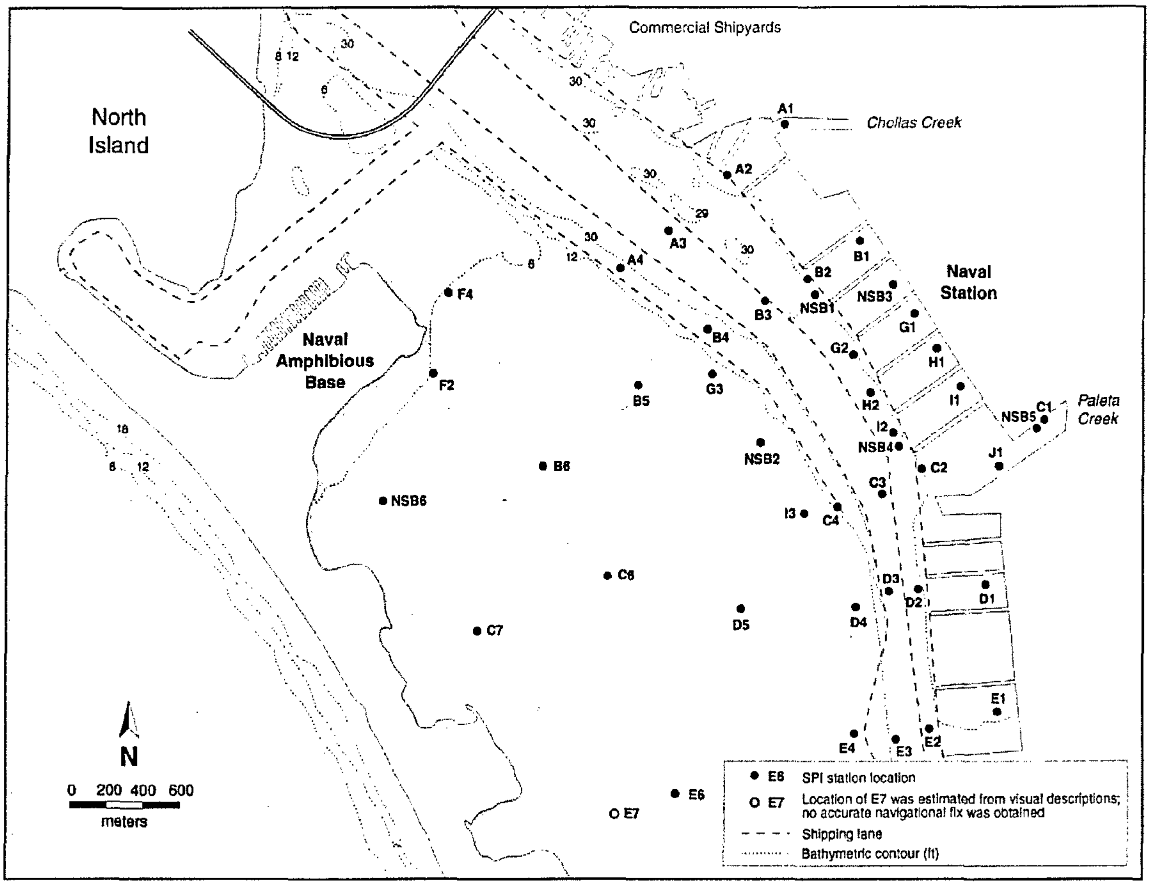

Figure 18. Stations from the July 1995 SPI survey selected for analysis.

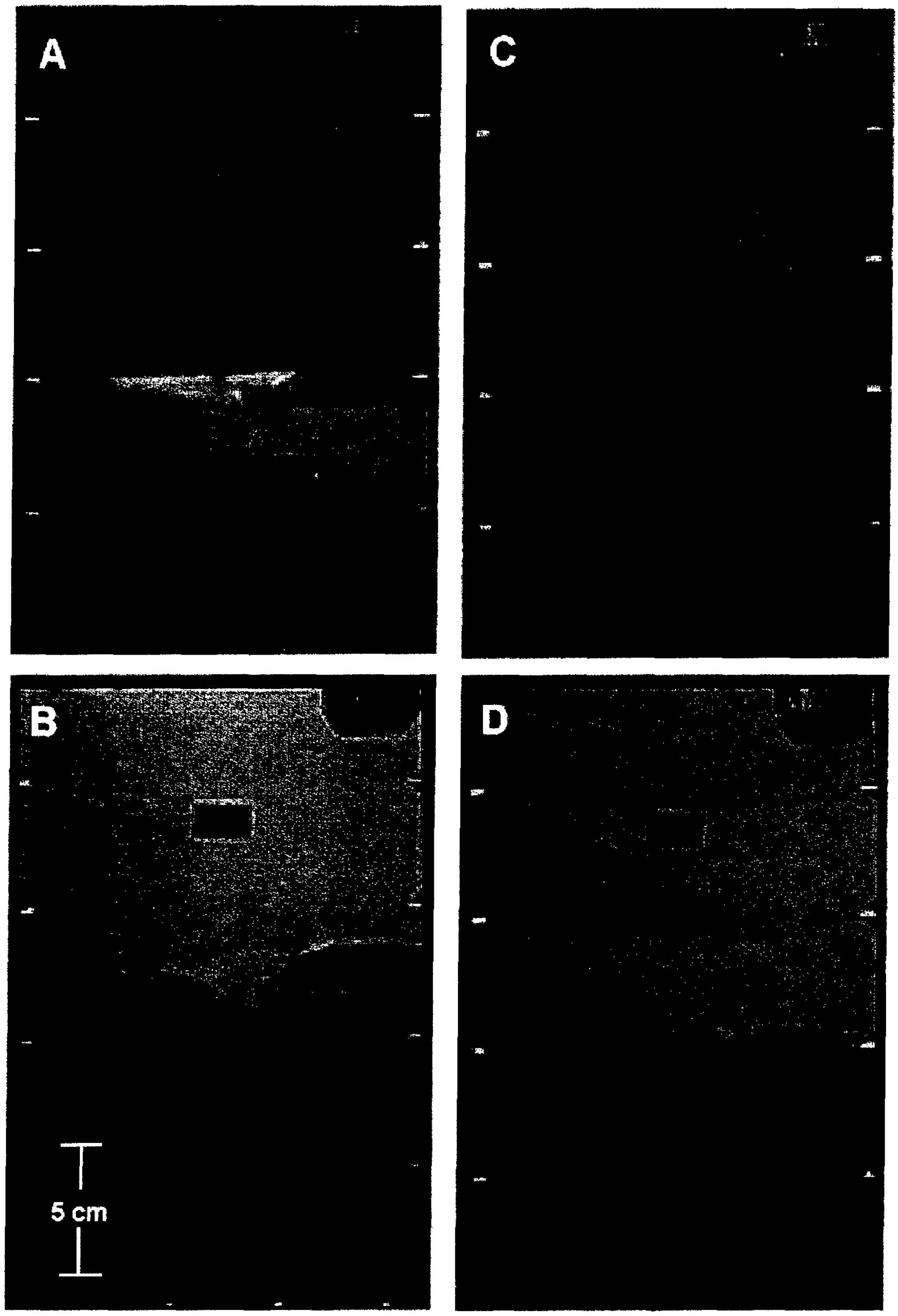

Figure 19. Images from four NSB stations showing a striking contrast in apparent sediment quality. Stations NSB-2 (A) and NSB-6 (B) indicate communities that appear to be unaffected by sediment contamination; in contrast, Stations NSB-3 (C) and NSB-5 (D) indicate signs of stressed habitat including shallow RPD, and the absence of organisms and burrows.

5.2.4 Spatial Distributions of Biological Effects

Assessment of the spatial distributions of biological effects was compiled based on several studies. Studies used in the spatial analysis include California State Water Resources Control Board [17], Anderson (1994), military construction (MCON) studies (1990–1994) [12], SAIC [14], and the current study. Table 12 summarizes the parameters used to distinguish effect thresholds. The thresholds were chosen based on the levels applied in the particular study. Where percent survival or mortality was measured, typical values of <80 percent or >20 percent were used (USEPA/USACoE, 1991). The benthic community disturbance index is based on indicator species and community parameters. All tests mentioned were from studies encompassing the NAVSTA shoreline and adjacent areas, as well as the western side of the bay.

Table 12. Characteristics used to compile the spatial maps for biological effects.

Test Species	**Study**	**Medium**	**Parameter**	**Significant Toxicity**	**Non-Significant Toxicity**
R. abronius	1,2	Sediment	% Survival	<80%	≥ 80%
Neanthes sp.		Sediment	% Survival	<80%	≥ 80%
S. purpuratus	1	Pore Water	% Normal Larval Development	<80%	≥ 80%
Haliotis sp.	1	Subsurface Water	% Normal Shell Development	<80%	>80%
G. japonica	3,4	Sediment	% Survival	<80%	≥ 80%
P450	2	Pore Water	Induction times Control	≥50	< 50%
C. gigas	2	Sediment Elutriate	% Larval Survival	<80%	≥ 80%
C. gigas	2	Sediment Elutriate	% Normal Larval Development	≤100% elutriate causing EC_{50}	No EC_{50} at 100% elutriate
Gonyaulax sp.	5	Pore Water	Light production	≤ 100% elutriate causing LC_{50}	No LC_{50} at 100% elutriate
Mysidopsis sp.	5	Sediment Elutriate	% Survival	≤100% elutriate causing LC_{50}	No LC_{50} at 100% elutriate
Menidia sp.	5	Sediment Elutriate	% Survival	≤100% elutriate causing LC_{50}	No LC_{50} at 100% elutriate
Skeletonema sp.	5	Sediment Elutriate	% Survival	≤100% elutriate causing LC_{50}	No LC_{50} at 100% elutriate

[1] *California State Water Resources Control Board study (1996)*

[2] *Environmental risk assessment support studies (Anderson 1994)*

[3] *Pre-dredging bioassays conducted under MCON projects (*Southwest Division Naval Facilities Engineering Command, *1994)*

[4] *Sediment Characterization Study (SAIC, 1994 Vol.1)*

[5] *Current Study*

The California State Water Resources Control Board study (1996) [17] summarizes several bioassay tests performed with several species. Effects were found for sediments throughout NAVSTA, specifically at Chollas Creek, the area between Piers 5 and 6, Paleta Creek, the south end of the Mole Pier, and the area south of Pier 13. Bioassays using an amphipod *(Rhepoxynius abronius)*, larvae of the sea urchin *(Strongylocentrotus purpuratus)*, and larval abalone (*Haliotis sp.*) indicated that sediments within the central bay and on the western side across from NAVSTA exhibited responses to the bioassay tests as well, although they are not located near similar input sources.

Environmental risk assessment support studies (Anderson 1994) indicated various responses with amphipod bioassays, oyster larvae survival and development, and enzyme induction using the cytochrome P450 system. The observation was made that a site at the quay wall between Piers 3 and 4, and another at the quay wall between Piers 11 and 12 contained sediments that showed responses measured by oyster larvae, amphipod, and enzyme testing. Effects were also measured at Chollas Creek and Paleta creek. Note that several sites in the center bay area demonstrated effects with the amphipod (*R. abronius*) test, and some effects were seen in the oyster larvae (*Crassostrea gigas*) tests as well. The Naval Amphibious Base sediments exhibited effects in amphipod tests and in oyster larvae development tests.

Pre-dredging bioassays conducted under MCON projects indicated that several sites between Piers 2 and 3 and between Piers 3 and 4 contained sediments that showed effects using amphipod bioassays (*G. japonica*). All sites located beyond the piers did not exhibit effects with the exception of one. The sites exhibiting effects within the pier area tended to be located near the mid-length of the piers and toward the quay wall.

The Sediment Characterization Study [14] provided extensive bioassay data with the amphipod *G. japonica* from sediment samples collected throughout NAVSTA. Testing using this species indicated sediments producing more widespread effects than noted with other species in other studies. Effects were seen in sediments from all piers, with the exception of the Chollas Creek area.

The data presented in figure 20 summarize bioassays performed as part of the current study with sediment elutriates (*Mysidopsis sp., Menidia sp., and Skeletonema sp.*), and pore water (QwikLite tests). These results are described in detail in section 5.2.2.

Two recent surveys of benthic community conditions were reviewed along with results from the current SPI study. The first study was performed by Merkel & Associates (1995) and focused on the biological characterization of candidate disposal sites for contaminated sediments. The study evaluated three regions of the bay within the NAVSTA area including a near-shore disposal site near Paleta Creek, and two potential confined disposal sites across the bay near the Silver Strand. Samples were analyzed from a total of 30 stations within these regions and characterized for benthic infaunal composition. The second survey was performed in conjunction with the previously mentioned California State Water Resources Control Board (1996) {17] study. A total of 75 stations within San Diego Bay were evaluated for benthic community structure. Table 13 summarizes the criteria used to identify the status of benthic community health for each study.

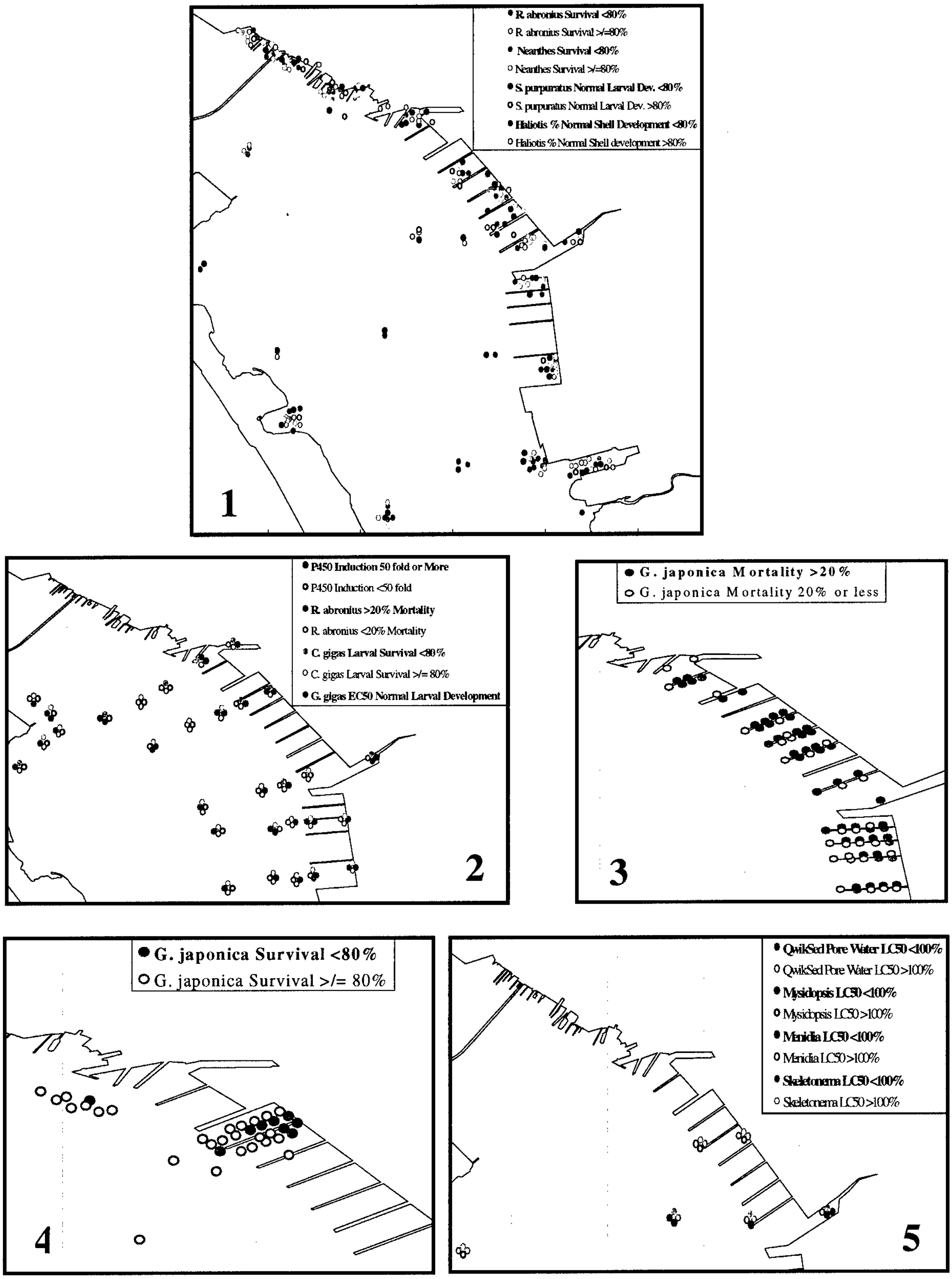

Figure 20. Spatial distribution of biological effects from five studies in table 12. Numbers in the figures correspond to the study designators listed in table 12.

Infaunal species evenness data were reviewed based on Merkel & Associates (1995). Station 30 exhibited the lowest species evenness index of all stations sampled. This was attributed to the extremely high abundance of *Capitella capitata.* This polychaete species is typically found in sediments having a high organic content. No other significant differences in species evenness or diversity were found among infaunal samples collected from the stations identified.

Table 13. Benthic community characteristics used to compile the spatial maps.

Test Species/ Medium	Parameter	Degraded	Transitional	Undegraded
Benthic Community (SWRCB, 1996)	Benthic Index	0	1	2
Organism-Sediment Index (Current Study)	OSI	< 6	N/A	≥ 6
Infaunal Species (Merkel & Assoc., 1995)	Species Evenness Index	< 0.65	N/A	≥ 0.65

Additional benthic community data were evaluated from the California State Water Resources Control Board study (1996). The benthic indices employed in that study indicated widespread benthic community disturbance throughout NAVSTA sediments. The commercial shipyards north of NAVSTA also exhibited several instances of benthic community disturbance, while sediments across the Bay on the western side south of the Naval Amphibious Base did not indicate benthic community degradation. The greater degree of benthic community difference noted in this data set is likely due to the more complex benthic analysis performed where in addition to diversity/evenness indices, analysis of habitat and species composition, dissimilarity matrices for pattern testing, assessment of indicator species, development of a benthic index, and cluster and ordination analysis were performed.

From the SPI demonstration, a spatial distribution of benthic habitat health can be mapped. Four independently measured SPI parameters are used to calculate a summary mapping statistic of benthic habitat health: apparent mean RPD depth, presence of methane gas, low/no dissolved oxygen at the sediment-water interface, and the infaunal successional stage. This statistic, known as the organism-sediment index (OSI), is used to indicate whether the benthic habitat has experienced physical disturbance, eutrophication, or excessive bioavailable contamination in the recent past. The highest possible OSI value is +11, which reflects a mature benthic community in relatively undisturbed conditions (generally, a good yardstick for high benthic habitat quality). These conditions are characterized by deeply oxidized sediment, with a low inventory of anaerobic metabolites and low sediment oxygen demand, and by the presence of a climax (Stage III) community.

The lowest possible OSI value is -10, which indicates that the sediment has a high inventory of anaerobic metabolites, a high oxygen demand, and no living organisms present. OSI values of six or less typically indicate that the benthic habitat has experienced some type of degradation. Figure 21 shows the spatial distribution of OSI values throughout the study area. About half of all the images analyzed had OSI values greater than 6. Except for two stations sampled at the mouth of Paleta Creek, the stations with the lowest OSI values seemed to be concentrated in the area to the east of the Naval Amphibious Base and west of the mouth of Chollas Creek.

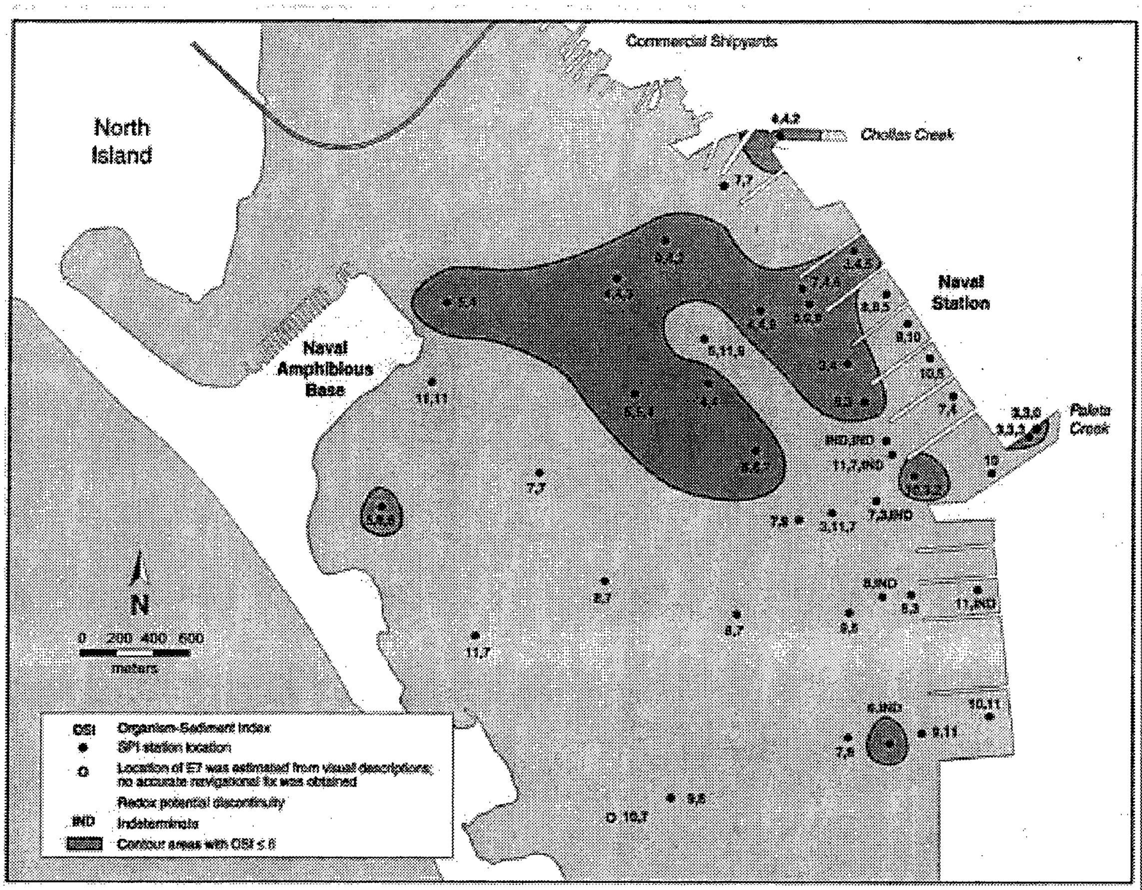

Figure 21. OSI values for each replicate analyzed. The OSI indicates whether the benthic habitat has experienced physical disturbance, eutrophication, or excessive bioavailable contamination in the recent past.

5.2.5 Summary of Bioassay and Benthic Community Studies

Bioassay studies have been performed throughout the bay, generally on in-place sediments primarily associated with dredging operations. Several of the recent bioassay and benthic community studies were listed for reference. Therefore, this study focused on suspended-phase and pore water testing. These test results showed that only sediments from Stations NSB-2, NSB-4, and NSB-5 (see figure 1) would produce any effects due to leaching of contaminants, or from possible resuspension of the sediments due to ship movements. Of the chemicals of concern in NAVSTA sediments, zinc showed the strongest tendency for

remobilization from benthic fluxes while cadmium, copper, nickel, lead, and zinc all exhibited remobilization during resuspension experiments. Bioavailability and, hence, specific bioassay tests, may be influenced by such factors as sediment grain size, AVS presence, and TOC, thus complicating analysis (Long et al., 1995). The fact that effects were not observed at stations with the highest metals (e.g., Station NSB-3) may indicate that the bioavailable fraction as discussed in previous sections is below the toxic level. Additionally, several factors complicate interpretation of observed effects in sediment and possible source inputs, whether from historical or current sources. For instance, the presence of naturally occurring ammonia in sediment elutriates suggest that it may be a contributing factor in observed effects rather than metals.

Spatial distributions of biological effects in the NAVSTA region were compiled based on several studies. These studies presented results ranging from no observed effects to toxicity and habitat disturbance, depending upon the species and parameters used. However, the sediment profiling image study indicated that the sediment quality and benthic habitat in the NAVSTA region were within what would be considered the normal range, given the water depth, amount of vessel traffic, and range of activities associated with operation of a naval station.

The general observation that emerges from the various chemical and biological results reviewed in this study suggests that a weight-of-evidence approach utilizing multiple species bioassay studies and chemical data are necessary to identify or predict sediment toxicity in a given area. All too often, some bioassay tests have indicated toxicity, while others have not. Additionally, the agreement between sediment pollutant concentrations and sediment toxicity do not always correlate particularly well with single chemical species, thus making it necessary to look further for sources of environmental impact.

5.3 IN-SITU BIOACCUMULATION AND BIOMARKER STUDIES

The bioaccumulation of sediment and water-associated chemicals, and biological responses elicited as a consequence of chemical exposure were examined at NAVSTA stations and adjacent reference stations. The mussels, *Mytilus edulis* and *Musculista senhousia*, collected at established reference locations, were transplanted at six stations in and around the NAVSTA for a study period of approximately 30 days. *Mytilus edulis*, being water column filter feeders, were deployed 1 m above the bottom and *Musculista senhousia*, infaunal mussels that are abundant in mud, were placed in the sediments. The water column studies were conducted in the early summer of 1995, and the infaunal study in the late summer of 1997. Tissue chemical concentrations were determined for silver, arsenic, cadmium, chromium, copper, mercury, nickel, lead, zinc, PCBs, pesticides, and total PAHs, both prior to transplantation and again after the 30-day exposure period. Sediments were measured for the same list of chemicals for comparison. Tissue and sediment chemical concentrations at the different stations were statistically compared to the Reference Station (Station NSB-6) and presented in table 15.

In conjunction with the bioaccumulation measurements, the growth of transplanted organisms was measured as well as a stress sensitive biochemical indicator known as a biomarker. In this case, the extent of damage to genetic material, or DNA, in the cells of the deployed mussels was the biomarker measured. DNA damage was determined by a technique commonly known as the single-cell gel electrophoresis method, or the Comet assay, which has

proven to be a rapid, versatile, and easily utilized tool for collecting data on DNA strand breakage and has the benefit of requiring relatively few cells (10,000) to perform. Together with chemistry measurements, the bioaccumulation, growth, and biomarker measurements help address chemical bioavailability and the biological effects of exposure at the cellular, organismal, and potentially at the population levels of biological organization.

5.3.1 Description and Relevance of Biomarkers

Organisms are often exposed to many types of stressors in their environment, yet have a limited capacity to adapt to stress-induced damage without adversely affecting such significant processes as growth and reproduction. Damage can be introduced by intrinsic processes, extrinsic chemicals, and radiation. Specifically, exposure to chemicals can result in increases in DNA damage and repair activity, as well as increases in cell turnover rates (Steinert, 1996; Olive, 1993), which can contribute to observed DNA strand breakage. The integrity of an organism's genetic material is the ultimate focal point for gauging the health and future success of that organism. This is because one of the resulting effects of sustained DNA damage is that the organism and/or its offspring may not survive.

One advantage of the Comet assay is that, in addition to detecting DNA strand breaks, other cellular features may be determined. For instance, with the use of image analysis software, normal tissue (somatic) cells that can repair themselves may be distinguished from sperm (germ) cells that cannot repair themselves. Somatic cells are generally designated as G1 or G2 cells depending upon the amount of DNA within the cell. The differences in DNA damage levels found in the somatic and germ cell populations can be used to estimate DNA repair activity. Together these measurements give a comprehensive picture of the effects of chemical exposure. In addition, cells in the process of normal cellular turnover can be identified.

The Comet assay also indicates detrimental effects of PAHs when an organism is exposed to sunlight. The effects of UV photoactivation on the toxicity of PAHs is well documented (Zepp, 1979; Bowling et al., 1983; Nikolaou, 1984; Huang, 1993; Ankley, 1994; Gala, 1994; Monson, 1995). PAHs, accumulated in tissue and photoactivated, can damage a cell's proteins, lipids, and DNA. Previous studies have established that the toxicity of photoactivated PAHs results from activation of accumulated PAHs, not externally activated and sequestered PAHs (Bowling et al., 1983; Small et al., 1967). The presence of these UV-sensitive and toxic compounds indicates that this mechanism should be routinely considered when investigating the impact of PAHs. To examine the diagnostic potential of UV activation of PAHs in conjunction with the Comet assay, cell samples were exposed to low levels of UV light for 30 minutes and then processed for Comet analysis. Significant increases in DNA damage levels resulting from this treatment were then compared to PAH bioaccumulation results.

5.3.2 Summary of Bioaccumulation and Biomarker Study Results

A summary of the bioaccumulation and biomarker results is provided below, along with a discussion of the sediment chemistry results presented in section 5.1.2. Statistical analyses are used throughout this section; therefore, a brief explanation follows. In statistical analysis, P values are used for the comparison of a measured variable in two groups. The P value is the probability of randomly obtaining samples with a mean difference as large, or larger, than would be observed if the null hypothesis were true. P is a probability and, therefore, has a

value ranging from 0.0 to 1.0. The lower the P value, the less likely that chance alone caused the difference observed. A P of 0.05 was arbitrarily chosen as the statistical significance threshold. A $P<0.05$ means that there is a 5 percent chance that a random sample would result in a difference large enough to be considered significant.

Sediment Chemistry. In contrast to the sediment chemical levels measured in 1995, evidence of a steep concentration gradient within the NAVSTA, decreasing with distance from the quay wall, was not as clear-cut in 1997. In general sediments along the Pier 4 transect contained higher concentrations of metals and PAHs than the Paleta Creek stations. Metals concentrations were little changed or slightly lower at Stations NSB-4 and NSB-5, compared to 1995. PAH levels were reduced at Station NSB-4 and higher at NSB-5, with the overall outcome of the measured concentrations being essentially equal in magnitude at both stations (table 14). The Reference Station was found to contain chemicals at similar or slightly lower levels than 1995, with the exception of cadmium, which was found at nearly double the 1995 concentration, 0.31 $ng \cdot g^{-1}$ in 1997 as compared to 0.17 $ng \cdot g^{-1}$ in 1995. The metals found above reference levels at the Paleta Creek stations were different for each station. Cadmium and lead were higher at Station NSB-5, and chromium, copper, and mercury at Station NSB-4 (table 14). Both stations had higher PAH concentrations than the Reference Station sediments (tables 14 and 15).

Along Pier 4, metals concentrations were lower at Station NSB-3 and relatively unchanged at Station NSB-1 in 1997, which once again resulted in no significant difference in overall metal concentrations between the two stations (table 14). Station NSB-3 sediments had elevated levels of arsenic, cadmium, copper, mercury, lead, zinc, and total PAHs relative to Reference Station NSB-6. Station NSB-1 had elevated levels of silver, cadmium, chromium, copper, mercury, lead, zinc, and total PAHs (tables 14 and 15).

Regardless of sediment concentration, infaunal mussel (*M. senhousia*) tissues at all NAVSTA stations had copper and mercury concentrations higher than the Reference Station tissues. Usually, however, chemicals in excess in the tissues were those found at higher levels in the sediments. The exception was Station NSB-3, which had higher tissue burdens of nickel that were elevated in the station sediments relative to the Reference Station (table 15). Similarly, arsenic was elevated in Station NSB-4 tissues, though not significantly higher in that station's sediments (table 15).

Only three stations were analyzed for pesticides and PCBs in 1995, Stations NSB-4, NSB-5, and NSB-6. Station NSB-4 had higher PCB concentrations than the Reference Station. All stations were analyzed for PCBs and pesticides in 1997, and the levels of these chemicals were elevated at all of the NAVSTA sites and showed evidence of a gradient, with concentrations decreasing with distance away from NAVSTA (table 15).

Table 14. Chemical concentrations in sediment (metals - $ug \cdot g^{-1}$ dry wt, TPAH - $ng \cdot g^{-1}$ dry wt) for *Mytilus edulis* stations, 1995, and *Musculista senhousia* stations, 1997.

***Mytilus edulis* Stations, 1995**										
Station	**Ag**	**As**	**Cd**	**Cr**	**Cu**	**Hg**	**Ni**	**Pb**	**Zn**	**TPAH**
NSB-1	1.11	16.9	0.8	94.8	249.3	1.17	23.4	130.0	483	ND
NSB-2	0.62	7.5	0.2	57.1	83.4	0.48	11.0	38.3	161	ND
NSB-3	3.04	26.3	5.3	111.5	503.0	1.37	43.5	153.5	661	ND
NSB-4	1.07	13.1	0.4	75.3	180.0	0.52	22.4	56.7	280	94237
NSB-5	0.88	10.2	1.4	76.4	159.0	0.60	22.0	116.5	401	16887
NSB-6	0.86	8.9	0.2	65.7	75.7	0.46	15.9	41.6	189	536
***Musculista senhousia* Stations, 1997**										
Station	**Ag**	**As**	**Cd**	**Cr**	**Cu**	**Hg**	**Ni**	**Pb**	**Zn**	**TPAH**
NSB-1	3.17	14.7	1.56	109.3	270.0	1.17	22.0	90.7	579	159767
NSB-2	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
NSB-3	1.96	36.2	1.00	107.0	308.0	0.57	19.2	99.7	410	135020
NSB-4	1.10	10.1	0.30	73.8	174.0	0.47	18.6	53.2	277	51673
NSB-5	0.72	7.4	1.06	59.5	123.0	0.32	16.7	94.5	313	45850
NSB-6	0.76	5.5	0.31	50.4	46.0	0.29	12.5	27.6	153	533

Note: ND indicates no data. In 1997, Station NSB-2 was stolen.

Table 15. Comparison of tissue and sediment chemistry data for *M. edulis* (M. e.) stations, 1995, and *M. senhousia* (M. s.) stations, 1997. X indicates that chemicals are statistically higher levels than the Reference Stations.

Station	Chemical	Sample Tissue (M.e.)	1997 Sediment	Sample Tissue (M.s.)	1995 Sediment
NSB-1	Ag				X
	As	X			
	Cd				X
	Cr	X	X		X
	Cu	X	X	X	X
	Hg	X	X	X	X
	Ni	X			
	Pb		X		X
	Zn	X	X		X
	PCBs				X
	Pesticides				X
	TPAH	X		X	X
NSB-3	Ag		X		
	As	X	X	X	X
	Cd		X	X	X
	Cr	X	X		X
	Cu	X	X	X	X
	Hg	X	X	X	X
	Ni	X	X	X	
	Pb		X	X	X
	Zn		X		X
	PCBs				X
	Pesticides				X
	TPAH	X			X
NSB-4	Ag				
	As	X		X	
	Cd				
	Cr	X			X
	Cu			X	X
	Hg			X	X
	Ni	X			
	Pb				
	Zn				
	PCBs		X		X
	Pesticides				X
	TPAH	X	X		X
NSB-5	Ag				
	As	X			
	Cd		X	X	X
	Cr	X			
	Cu			X	
	Hg			X	
	Ni	X			
	Pb	X	X	X	X
	Zn	X	X		
	PCBs				X
	Pesticides	X		X	X
	TPAH	X	X	X	X

*Note: NSB-2 and NSB-6 are reference stations not shown; *Dunnett's test, significance at P<0.05*

Bioaccumulation, Growth, and DNA Damage. The following section discusses the results of the experiments in 1995 (*Mytilus edulis*) and 1997 (*Musculista senhousia*) with respect to bioaccumulation, growth, and DNA damage. Sediment chemistry data and tissue concentrations are also compared. The reference stations are compared with other study stations, and Paleta Creek and Pier 4 are explicitly addressed.

Reference Station. In the 1995 *Mytilus edulis* study, it was found that Reference Station NSB-6 on the west side of the bay was identified as the least impacted of the six stations by all measures. Reference Station NSB-2, located in the middle of the channel, was identified as the station of second lowest impact by sediment chemistry, bioaccumulation, and growth. All NAVSTA stations had growth lower than Station NSB-6 (table 16). Mussels at Station NSB-1 had the lowest growth of all. Statistical comparisons between NAVSTA stations (Stations NSB-1 through NSB-5) and the Reference Station (Station NSB-6) were made for tissue concentrations of silver, arsenic, cadmium, chromium, copper, mercury, nickel, lead, zinc, PCBs, pesticides and total PAHs. There were no statistically significant differences ($P>0.05$) between the stations for silver and cadmium in that tissue levels were the same as those measured at the Reference Station. Concentrations were elevated at all stations (Stations NSB-1 through NSB-5) in relation to the Reference Station (Station NSB-6) for arsenic, chromium, nickel, and total PAHs. Copper and mercury were only elevated at Stations NSB-1 and NSB-3 (tables 15 and 17). Lead and pesticide levels were elevated at Station NSB-5, and zinc tissue levels at Stations NSB-1 and NSB-5 (tables 15 and 17).

Table 16. Growth results of *Mytilus edulis* deployed in 1995

Station	Days of Growth	Weight % Difference	Weight %Diff/Day	Length % Difference	Length %Diff/Day
NSB-1	33	9.1 ± 9.8	0.28	4.1 ± 2.7	0.12
NSB-2	32	23.6 ± 10.5	0.74	7.7 ± 3.6	0.24
NSB-3	32	15.7 ± 5.6	0.49	6.1 ± 2.6	0.19
NSB-4	33	21.9 ± 15.2	0.66	8.8 ± 5.9	0.27
NSB-5	33	18.3 ± 6.7	0.55	7.0 ± 4.8	0.21
NSB-6	32	32.0 ± 12.8	1.00	11.1 ± 5.0	0.35

Results using *Musculista senhousia* in 1997 were consistent with those of *Mytilus edulis*. Station NSB-2 was stolen so no data are available at that location. Survival and growth were higher at Station NSB-6 (table 18), although the results were highly variable. DNA damage levels were consistently the lowest. *M. senhousia* generally accumulated metals at higher concentrations than *M edulis* (table 17). This is a common relationship found when comparing sediment-dwelling organisms and those up in the water column. Levels of PAHs detected in *M. senhousia* tissues were within the same range as *M. edulis.* In comparison to tissue concentrations found at the Reference Station (Station NSB-6), PAHs were higher in the tissues of infaunal mussels (*M. senhousia*) at Stations NSB-1 and NSB-5. Similar to *M. edulis* results, pesticides were elevated in mussels at Station NSB-5. All stations (Stations NSB-1 through NSB-5) were higher in levels of copper, with no significant differences for silver, chromium, and zinc at any of the stations. Other metals were elevated at specific stations. Cadmium and lead were higher at Stations NSB-3 and NSB-5, arsenic at Stations

NSB-3 and NSB-4, mercury at Stations NSB-1, NSB-3, and NSB-4, and nickel at Station NSB-3 (See tables 15 and 17).

Paleta Creek. Bioaccumulation results for *Mytilus edulis* indicate very high levels of PAHs and the Comet assay identified a significant impact when UV photoactivation and expression of PAH toxicity were considered. The possible involvement of PAH photoactivation was explored by examining resident organisms using the Comet assay. The results from those experiments showed that *Mytilus edulis* can bioaccumulate high concentrations of PAHs with little impact in the absence of sunlight. However, exposure to ambient sunlight activates the accumulated PAHs and results in high levels of DNA damage. The mouth of Paleta Creek had high PAH sediment loads and flux rates, though this was not reflected by growth or bioaccumulation results. However, Comet germ cell data did indicate an impact above that anticipated by sediment metal exposure alone, and somatic cell results revealed a high capacity for repair indicative of PAH exposure in animals under low PAH activation conditions (low light exposure). PCBs, though elevated in the sediments at Station NSB-4, were not elevated in the tissues of the mussels at that station or any other station. Mussels at only Station NSB-5 had bioaccumulated notable concentrations of pesticides (table 15).

Table 17. Chemical bioaccumulation in *Mytilus edulis* tissues, 1995 and in *Musculista senhousia* tissues, 1997 (metals - $ug \cdot g^{-1}$ dry wt., TPAH - $ng \cdot g^{-1}$ wet wt.).

***Mytilus edulis* Stations, 1995**										
Station	Ag	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn	TPAH
T 0	0.04	8.05	2.08	1.20	11.00		1.67	1.62	130.00	330
NSB-1	0.07	9.62	4.09	1.38	14.35	0.07	0.58	1.29	192.2	2587
NSB-2	0.06	8.19	4.06	1.28	8.27	0.06	0.54	1.06	152.15	710
NSB-3	0.09	9.51	3.16	1.19	21.45	0.07	0.58	1.26	156.8	3701
NSB-4	0.06	9.77	3.62	1.35	10.45	0.06	0.63	1.17	156.2	5248
NSB-5	0.05	8.72	2.63	1.23	10.75	0.04	0.56	2.00	175.2	1620
NSB-6	0.06	7.11	2.19	0.89	7.39	0.06	0.35	0.97	134.2	403
***Musculista senhousia* Stations, 1997**										
Station	Ag	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn	TPAH
NSB-1	0.95	13.12	0.95	2.74	60.2	0.179	2.42	3.7	109.4	3535
NSB-2	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
NSB-3	1.07	14.84	1.31	4.99	95.57	0.21	3.81	6.52	127.17	1639
NSB-4	0.92	14.13	0.92	2.87	53.1	0.157	3.37	3.69	136.9	1356
NSB-5	1.09	12.79	1.48	2.29	78.6	0.126	2.29	10.84	101.5	3246
NSB-6	0.76	12.46	0.80	2.90	38.18	0.15	2.46	3.19	91.50	904

Note: T 0 indicates measurements taken at Time 0. ND indicates no data. In 1997, Station NSB-2 was stolen.

Musculista senhousia inside Paleta Creek (Station NSB-5), as well as at the end of Pier 4 (NSB-1), bioaccumulated PAHs at concentrations two to four times higher than *M. senhousia* at the other stations (table 17). Upon UV treatment, DNA damage increased above

background levels in the germ cells of the organisms at only these stations. These *M. senhousia* appear to be more sensitive to PAHs than *M. edulis.* Higher DNA damage in the germ cells correlates very well with increased PAH uptake (figure 22). *M. senhousia* maintains a higher level of DNA damage in the presence of PAHs and the absence of light. These organisms may therefore possess a higher capacity than *Mytilus* for the activation of these compounds. UV treatment resulted in a twofold increase in DNA damage in samples from Stations NSB-1 and NSB-5. As with *M. edulis,* PCB concentrations were not elevated, but pesticide concentrations were elevated in mussels from Station NSB-5 alone (table 15).

Table 18. *Musculista senhousia* growth during deployment #1, 1997.

Station	Station	Mussel Count	Survival	Growth % Weight Gain	Growth % Length Gain
NSB-1-1	1(1)	150	97%	18.0	14.3
NSB-1-2	1(2)	150	56%	26.7	4.5
NSB-1	**Mean =**		**76%**	**22.4**	**9.4**
NSB-3-1	3(1)	150	79%	12.0	5.5
NSB-3-2	3(2)	140	74%	5.1	4.3
NSB-3-3	3(3)	150	73%	0.0	0.0
NSB-3-4	3(4)	140	82%	13.3	0.0
NSB-3-5	3(5)	140	94%	28.0	7.5
NSB-3-6	3(6)	150	81%	20.0	5.9
NSB-3	**Mean =**		**80%**	**13.1**	**3.9**
NSB-4-1	4(1)	140	61%	0.0	3.1
NSB-4-2	4(2)	150	67%	36.0	11.8
NSB-4	**Mean =**		**64%**	**18.0**	**7.5**
NSB-5-1	5(1)	150	70%	0.0	0.0
NSB-5-2	5(2)	150	70%	60.0	12.2
NSB-5	**Mean =**		**70%**	**30.0**	**6.1**
NSB_6-1	6(1)	150	84%	38.7	13.1
NSB-6-2	6(2)	150	77%	10.0	12.7
NSB-6-3	6(3)	140	92%	48.0	9.9
NSB-6-4	6(4)	150	78%	48.0	11.3
NSB-6-5	6(5)	140	92%	48.0	11.8
NSB-6-6	6(6)	140	81%	62.7	13.4
NSB-6	**Mean =**		**84%**	**42.6**	**12.0**

Pier 4. Results from *Mytilus edulis* studies show that Stations NSB-1 and NSB-3 were the two most impacted stations by all measures. Sediment chemistry and bioaccumulation data indicate metals, mercury, copper, and zinc as the most notable chemicals. Comet and growth results also consistently indicate adverse biological effects at these two stations (figure 23).

Compared to the earlier *M. edulis* study, *Musculista senhousia* bioaccumulates higher concentrations of most metals than *M. edulis*, particularly copper. Copper concentrations can be over five times higher in *M. senhousia* than in *M. edulis*. However, *M. senhousia* appears to be far less susceptible to the toxic effects of metals. As mentioned above, mussels at sta-

tions NSB-1 and NSB-5 had bioaccumulated high concentrations of PAHs (table 17). These two stations were the only two with higher levels of DNA damage and showed increases in DNA damage following photoactivation treatment, which is in agreement with the PAH bioaccumulation results (figure 24).

5.3.3 Summary Discussion

The growth, bioaccumulation, and DNA damage results from mussels deployed at Reference Station NSB-6 were similar to mussels of the same species at their original collection sites and under optimum conditions in flow-through seawater aquaria. The organisms at the Reference Station were therefore felt to represent populations under little or no stress. DNA damage levels responded rapidly to chemicals at the deployed stations. Test organisms must be chosen carefully, as is illustrated by the lack of response to PAHs without light, and sensitivity to metals, of *M. edulis,* in contrast to *M. senhousia's* relative insensitivity to metals and sensitivity to PAHs. In both organisms, germ cell DNA damage was higher at certain stations. When exposed to metals, *M. edulis* showed affects in both germ and somatic cells, revealing an impact at the cellular level. The most impacted stations were stations with significant DNA damage and growth affects (table 16) along Pier 4 and inside Paleta Creek.

The growth of the infaunal mussels *(M. senhousia)* at all NAVSTA stations was lower than the Reference Station (table 18). Yet only two stations had significant levels of increased DNA damage, observed strictly in the germ cells (table 19). DNA damage is indicated by a measure of the tail moment of the cell, which shows a difference between germ cell damage in the NAVSTA stations versus the Reference Station. The tail moment describes the distribution of DNA away from the nucleus of the cell with a higher moment indicating greater damage. This pattern of damage, germ cell damage without corresponding somatic damage, was observed at sites with elevated PAHs, as seen with *M. edulis* at Station NSB-4 in 1995 and infaunal mussels *(M. senhousia)* in 1997. The mechanisms for coping with these chemicals appear to have an energetic cost resulting in lower rates of growth and survival.

In general, bioaccumulation results indicated that metals and hydrocarbons are available to filter feeding organisms at these NAVSTA stations. PCBs were not bioaccumulated at levels greater than at the Reference Stations, and pesticides were available and elevated in the tissues of both mussel species at Station NSB-5. It appears the water column filter feeders (*M. edulis*) were primarily affected by suspended sediments. This assumption is made because the comparison of bioaccumulation in *M. edulis* to water, porewater, and sediment chemistry, shows the highest covariation with the sediments. Although these organisms were suspended above the water, they appeared to be coming into contact with contaminants and resuspension is a possible mechanism for the observed bioavailability. Measured chemicals are present at elevated concentrations in the sediments, though not always bioavailable at levels mortally harmful to living organisms. This is evidenced by PAH concentrations observed in the sediments at Station NSB-3, yet not bioaccumulated by infaunal mussels (*M. senhousia*) to the same extent as at Stations NSB-1 and NSB-5. The highly variable growth and survival observed for the *M. senhousia* only meters apart at the same stations may indicate that chemical bioavailability is sensitive to localized influences such as sediment resuspension (table 18).

As *M. edulis* appears to be more sensitive to metals, the areas of greatest impact were at the stations along Pier 4 where the highest sediment metal concentrations were found. The sediment-dwelling *M. senhousia* were more sensitive to PAHs and responded significantly at the

stations where high concentrations of PAHs were in the sediments and bioavailable along Pier 4 and inside Paleta Creek.

Table 19. *Musculista senhousia* growth and DNA damage during deployment #2, 1997. Tail moment figures are presented as the mean plus or minus the standard deviation with number of cells in parentheses. Higher tail moment values indicate greater damage.

			Growth		DNA Damage (Tail Moment)		
Station	**Mussel Count**	**Survival**	**% Weight Gain**	**% Length Gain**	**Germ**	**G1**	**G2**
NSB-1	50	61	1.5	0.0	9.3 ± 1.1 (60)***	2.4 ± 0.3 (179)	3.0 ± 1.4 (11)
NSB-2	ND	ND	ND	ND	ND	ND	ND
NSB-3	50	76	0	0.0	6.0 ± 0.5 (147)*	2.8 ± 0.4 (94)	4.7 ± 2.9 (9)
NSB-4	50	74	0	0.0	5.5 ± 0.7 (99)	2.5 ± 0.4 (139)	2.4 ± 1.0 (12)
NSB-5	50	65	12.1	3.0	9.1 ± 1.1 (52)***	2.6 ± 0.3 (187)	3.8 ± 1.3 (11)
NSB-6	50	87	63	12.8	4.0 ± 0.7 (74)	2.9 ± 0.4 (155)	3.1 ± 1.1 (21)
					* P<0.05;	***P<0.001	

Notes: *ND indicates no data. Germ cells are sperm cells, which do not have repair capabilities. Normal tissue (somatic) cells are designated G1 or G2 cells, depending upon the amount of DNA within the cell. * P<0.05 indicates that there is a 5 percent chance that a random sample would result in a difference large enough to be considered significant; ***P<0.001 indicates that there is a 0.1-percent chance that a random sample would result in a difference large enough to be considered significant.*

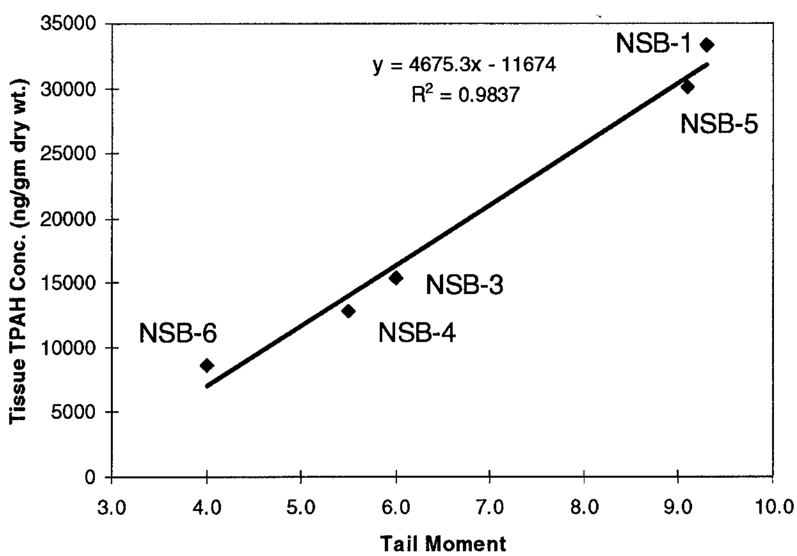

Figure 22. Covariation of DNA damage in germ cells with tissue PAH burdens in *M. senhousia*. Tail moment is a measure of DNA damage; higher values correspond to greater damage.

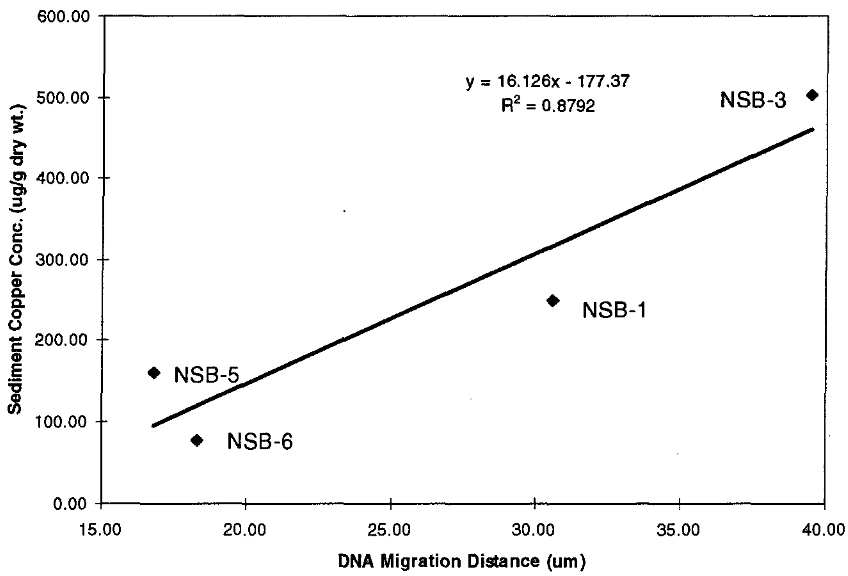

Figure 23. Covariation of DNA damage in germ cells with sediment copper burdens in *M. edulis*. DNA migration distance is a measure of DNA damage; higher values indicate greater damage.

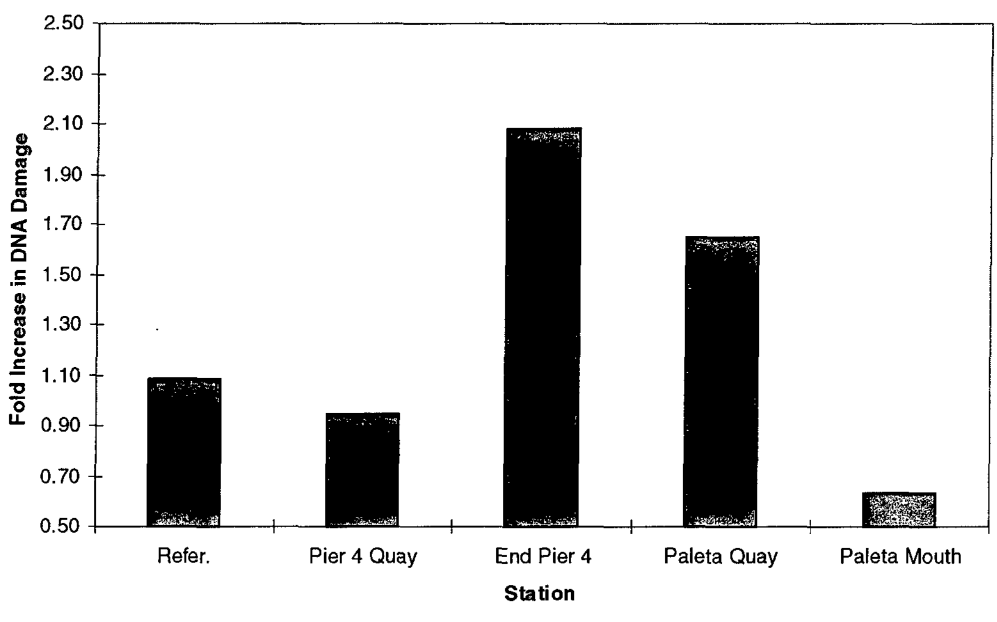

Figure 24. Fold increase (multiplier) in DNA damage after UV exposure of *M. senhousia* tissues. Tissues from the end of Pier 4 and inside Paleta Creek had higher levels of damage induced by UV exposure (P< 0.01).

5.4 REGIONAL ASSESSMENT OF SEDIMENT QUALITY

A retrospective analysis of the entire sediment data set was performed to characterize the overall sediment quality of spatial regions within the NAVSTA area. The analysis draws from all the studies summarized in the previous sections. The analysis provides some guidance as to which spatial areas would be considered impacted or non-impacted based on the preponderance of the chemical and biological data considered individually and jointly. Because most of the studies measured only a limited subset of chemical and biological parameters, a site-by-site analysis of the data would require much of the available information be ignored. In addition, the heterogeneity of chemicals within the sediment, and the frequent redistribution of sediments by ship movements, suggest that a measurement made at a given point has only limited relevance in terms of spatial assessment.

To overcome some of these limitations, we attempted to divide the NAVSTA area into a limited number of subregions, each of which contained a substantial amount of chemical and biological data. The chemical and biological data within each subregion were then evaluated based on commonly applied screening effect thresholds. Within each subregion, the sediment quality was then judged based on a "weight of evidence" approach and the sediments within the NAVSTA area were classified spatially based on relative levels of impact from subregion to subregion. Figure 25 shows the locations of chemical and biological observations used in the analysis.

5.4.1 Identification of Spatial Subregions

Spatial subregions of the NAVSTA area were identified based on four primary considerations that included physical boundaries, mixing scales, chemical gradients, and data density.

The physical boundaries considered included the shorelines and shipping channel. These boundaries restrict the transport and redistribution of sediment and thus tend to isolate spatial areas. The lateral mixing scale for sediment transport in the NAVSTA area (especially within the piers) is thought to be controlled by resuspension events during ship movements (see section 6.3.2). Field measurements and modeling show that resuspended materials within the piers are transported primarily parallel to the shoreline due to tidal motion. Most resuspended material settled out over distances of several hundred meters, a distance equivalent to two to three pier spacings. Thus, an alongshore scale for subregions within the piers was established at two to three pier spacings. Investigations have also shown that a contamination gradient exists in the offshore direction from the shoreline, with highest levels near the quay wall and decreasing levels toward the shipping channel.

To isolate the near-shore areas of higher chemical levels, an offshore scale for the subregions was established at ½-pier length. This scale is also in keeping with the observed offshore scale of resuspension plumes from ship movement. Additional subregions were then identified by extending these regions out into the bay. The first subregion outside the piers was defined to extend from the end of the piers to the border of the shipping channel. Alongshore scales for these subregions were based on data density. Regions were identified across the bay in the shoal area in a similar fashion. Figure 26 shows the final locations of the subregions. In addition, because of the retrospective nature of the analysis, sample locations within the subregions were not necessarily selected at random, but may contain biases.

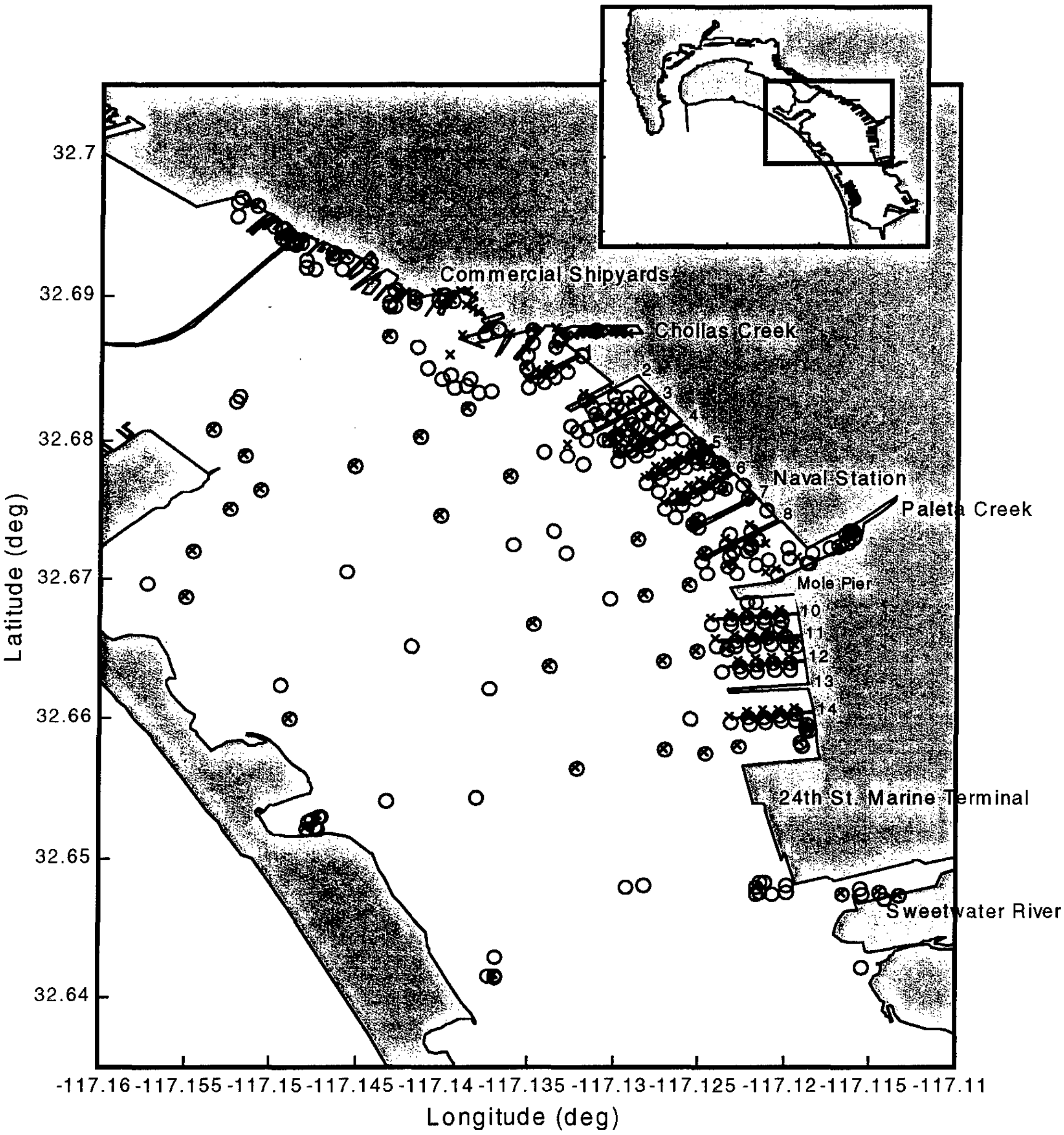

Figure 25. Location of the chemical (x) and biological (o) measurement sites used in the spatial analysis of sediment quality.

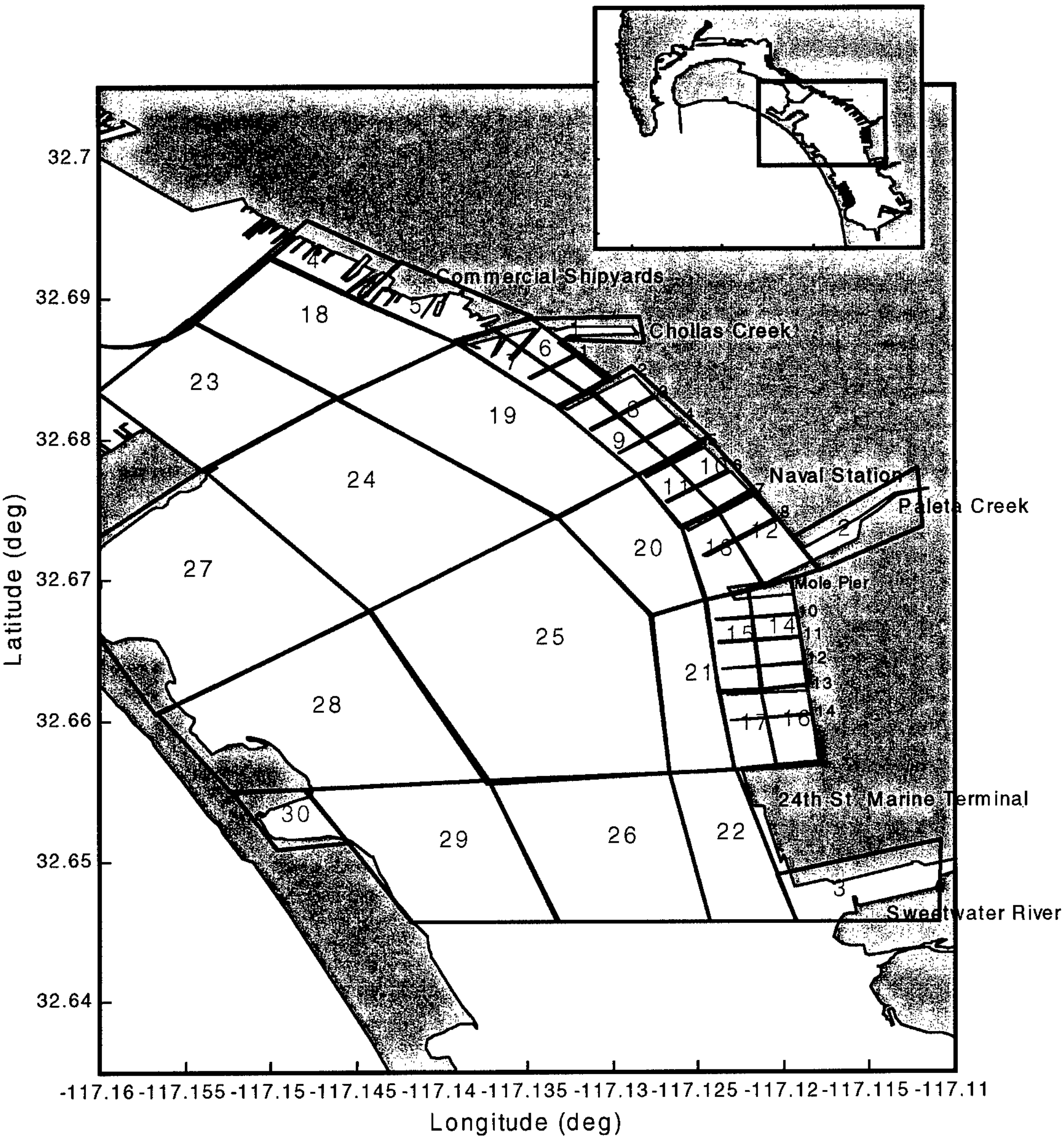

Figure 26. Spatial subregions defined for the NAVSTA area and surrounding regions.

5.4.2 Characterization of Sediment Quality

In previous sections we have described the existing knowledge of various sediment quality parameters in the NAVSTA region. Here, an attempt is made to integrate the results of those studies to provide a "weight of evidence" analysis of the overall sediment quality based on all available data. Because of the lack of specific regulatory criteria for sediment quality, this analysis should be interpreted as providing a relative measure of the sediment quality across the subregions defined above.

A set of rules were established for characterizing the sediment within each subregion based on all observations that fell within the subregion boundaries. For chemical measurements, an individual measurement was considered a "hit" if its concentration exceeded the ERM. For

effects observed during infaunal analysis, a measurement was considered a "hit" if it exceeded the threshold described in tables 12 and 13. The incidence of observations exceeding chemical and biological effect thresholds were then determined for each subregion. Tables 20 and 21 show analysis results, including the total number of measurements, the number of exceedences, and percent exceedence.

Table 20. Summary of results from all studies showing the total number of observations (n_{tot}), number of observations exceeding the ERM ($n_{>erm}$), and percent incidence of exceeding the ERM ($\%_{>erm}$) in each subregion for silver, cadmium, copper, mercury, and total PAH.

Sub-region	Ag			Cd			Cu			Hg			PAH		
	$n_{>erm}$	n_{tot}	$\%_{>erm}$	$n_{>erm}$	n_{tot}	$\%_{>erm}$	$n_{>erm}$	n_{tot}	$\%_{>erm}$	$n_{>erm}$	n_{tot}	$\%_{>erm}$	$n_{>erm}$	n_{tot}	$\%_{>erm}$
1	0	22	0	0	22	0	0	22	0	1	23	4	0	2	0
2	0	7	0	0	7	0	0	7	0	2	7	29	1	4	25
3	0	4	0	0	4	0	0	4	0	0	4	0	0	1	0
4	0	6	0	0	6	0	5	6	83	6	6	100	0	1	0
5	3	15	20	0	15	0	12	15	80	7	10	70	1	3	33
6	1	7	14	0	7	0	1	7	14	2	9	22	0	3	0
7	0	2	0	0	2	0	0	2	0	1	8	13	0	2	0
8	6	10	60	0	9	0	8	10	80	15	17	88	1	10	10
9	0	10	0	0	8	0	2	10	20	7	18	39	1	6	17
10	0	8	0	0	9	0	8	8	100	9	14	64	0	6	0
11	0	5	0	0	5	0	0	5	0	4	13	31	0	2	0
12	0	8	0	0	8	0	2	9	22	0	11	0	0	6	0
13	0	6	0	0	5	0	0	6	0	0	9	0	2	5	40
14	0	8	0	0	8	0	6	8	75	9	20	45	0	10	0
15	0	5	0	0	5	0	0	5	0	8	19	42	0	4	0
16	0	7	0	0	7	0	3	7	43	0	11	0	0	4	0
17	0	2	0	0	2	0	1	2	50	1	7	14	0	2	0
18	0	3	0	0	3	0	0	3	0	1	3	33	0	2	0
19	0	6	0	0	5	0	1	6	17	0	5	0	0	5	0
20	0	4	0	0	4	0	0	4	0	1	4	25	0	4	0
21	0	3	0	0	3	0	0	3	0	0	3	0	0	3	0
22	0	2	0	0	2	0	1	2	50	0	2	0	0	1	0
23	0	1	0	0	1	0	0	1	0	0	1	0	0	1	0
24	0	4	0	0	3	0	0	4	0	0	4	0	0	4	0
25	0	7	0	0	7	0	0	7	0	0	7	0	0	5	0
26	0	1	0	0	1	0	0	1	0	0	1	0	0	1	0
27	0	4	0	0	4	0	0	4	0	0	4	0	0	6	0
28	0	2	0	0	2	0	0	2	0	0	2	0	0	1	0
29	0	1	0	0	1	0	0	1	0	0	1	0	0	1	0
30	0	2	0	0	2	0	0	2	0	0	2	0	0	0	ID

Note: ID indicates insufficient data.

An even weighting for exceedences of individual chemicals can be produced by taking an overall average of percent exceedence for all chemicals (table 21). From this analysis, we find that the percent of sites within a subregion with concentrations exceeding the ERM ranges from a low of 0 percent in Subregions 3, 21, 23, 24, 25, 26, 27, 28, 29, and 30, to a high of 50 percent in Subregion 8. Biological effect results range from a low of 0 percent in Subregion 29 to a high of 80 percent in Subregion 26.

Table 21. Summary of results from all studies showing the total number of observations (n_{tot}), number of observations exceeding the ERM ($n_{>erm}$), and percent incidence of exceeding the ERM ($\%_{>erm}$) in each subregion for total PCB, lead, and zinc. The mean of the individual chemical incidence is also shown and the incidence of observed biological effects ($n_>$), the total number of biological effects measurements (n_{tot}), and the percentage of measurements with effects levels exceeding the effects threshold ($\%_>$).

Sub-region	PCB			Pb			Zn			All Contam.	Bio. Effects		
	$n_{>erm}$	n_{tot}	$\%_{>erm}$	$n_{>erm}$	n_{tot}	$\%_{>erm}$	$n_{>erm}$	n_{tot}	$\%_{>erm}$	mean $\%_{>erm}$	$n_>$	n_{tot}	$\%_>$
1	0	2	0	0	22	0	2	22	9	2	3	5	60
2	2	6	33	0	7	0	4	7	57	18	14	22	64
3	0	4	0	0	4	0	0	4	0	0	8	27	30
4	5	6	83	0	6	0	4	6	67	42	18	30	60
5	3	6	50	1	15	7	12	15	80	42	17	29	59
6	0	5	0	0	7	0	0	7	0	6	11	18	61
7	0	1	0	0	2	0	0	2	0	2	7	10	70
8	8	9	89	0	10	0	7	10	70	50	16	24	67
9	4	8	50	1	10	10	4	10	40	22	16	35	46
10	1	4	25	0	8	0	1	8	13	25	20	30	67
11	0	4	0	0	5	0	0	5	0	4	14	20	70
12	1	8	13	0	8	0	1	8	13	6	5	19	26
13	1	5	20	0	6	0	0	6	0	8	6	19	32
14	2	9	22	0	8	0	1	8	13	19	14	22	64
15	0	3	0	0	5	0	0	5	0	5	9	22	41
16	0	6	0	0	7	0	0	7	0	5	16	26	62
17	0	1	0	0	2	0	0	2	0	8	5	10	50
18	0	3	0	0	3	0	0	3	0	4	3	6	50
19	0	1	0	0	6	0	0	6	0	2	8	35	23
20	0	3	0	0	4	0	0	4	0	3	5	14	36
21	0	0	ID	0	3	0	0	3	0	0	7	17	41
22	0	2	0	0	2	0	0	2	0	6	9	15	60
23	0	0	ID	0	1	0	0	1	0	0	4	8	50
24	0	0	ID	0	4	0	0	4	0	0	10	19	53
25	0	1	0	0	7	0	0	7	0	0	9	31	29
26	0	1	0	0	1	0	0	1	0	0	4	5	80
27	0	4	0	0	4	0	0	4	0	0	6	12	50
28	0	2	0	0	2	0	0	2	0	0	1	5	20
29	0	1	0	0	1	0	0	1	0	0	0	2	0
30	0	2	0	0	2	0	0	2	0	0	7	22	32

Figure 27 shows the relationship between the frequency of exceedence of chemical and biological effects thresholds. Subregion incidences of biological effects are plotted on the Y-axis and subregion incidences of chemical concentrations above the ERM are plotted on the X-axis. The plot does not indicate toxicity or chemical levels, but rather the percentages of threshold exceedences within each subregion. It is significant to note that for low incidence of chemical exceedence, there is considerable scatter in the range of biological exceedences. However, for high incidence of chemical exceedence, the incidence of biological exceedence of biological thresholds is also generally high. This trend was also observed for comparison of individual chemicals to biological effects, and the ERM quotient and biological effects (not shown). Similar trends have been observed in previous studies as well when directly comparing chemical exposure and bioassay test results [17]. The explanation for this trend is not clear. As was found in the biomarker investigation, biological effects are dependent on the mechanism of toxicity, chemicals present, and organism used. At two stations, inconsistencies were resolved by identifying a mechanism of toxicity (PAH-photoactivation), in relation to a specific chemical, consistent with the organism used. Subregions where low incidence of contamination is observed but high incidence of biological effects still occur may be due to several factors. Differences in measurement locations, effects due to chemicals that were not measured, and effects due to variations in sediment composition such as grain size, may all contribute to this variability. Three groupings were identified from the plot in figure 27 and used for a relative comparison of subregions within the NAVSTA area. Table 22 describes this relative scale.

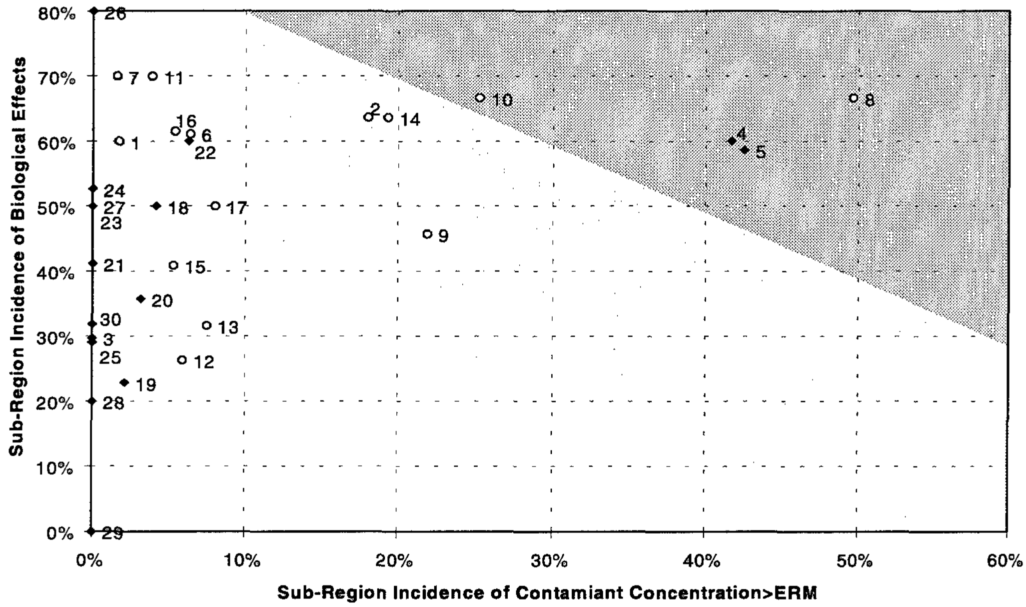

Figure 27. Comparison of percentage of exceedences of chemical and biological effect thresholds in the NAVSTA subregions. Three groupings indicated by the shaded areas (lightest shading–low to darkest shading–high) are measures of both potential chemical and biological impacts and are described in table 22. Open circles indicate subregions within the NAVSTA piers, and filled diamonds indicate stations outside the piers. Numbers next to the symbols indicate the subregions shown in figure 26.

Table 22. Relative scale of sediment quality based on exceedence of ERM and observed biological effects. I_{ERM} is the incidence of chemical observations exceeding the ERM and I_{EFF} is the incidence of observed biological effects within a given subregion.

Impact Scale	Incidence Condition
Low	$I_{ERM}+I_{EFF}$ <50%
Moderate	50%<$I_{ERM}+I_{EFF}$ <90%
High	90%<$I_{ERM}+I_{EFF}$

5.4.3 Sediment Quality Characteristics in the Subregions

Sediment chemical characteristics within the NAVSTA subregions were evaluated by calculating means and ranges of individual chemicals from all the sites within a given subregion. Subregions were then ranked from highest to lowest mean concentration for each chemical. The results of these rankings must be interpreted with some care because, as discussed previously, the various data sets included in the analysis may include biases in sampling strategies and methodologies that limit their applicability for spatial analysis. For example, the treatment of non-detect results was handled somewhat differently in some studies with some reporting the detection limit, some half the detection limit, and some zero. In general, these have been converted to half the detection limit although there were some cases where values were reported as zero and no detection limit was specified. Given the above caution regarding interpretation, the analysis indicates that average levels of silver exceeded the ERM in one subregion, and the upper range of silver levels exceeded the ERM in one subregion. For cadmium, no averages exceeded the ERM, though upper bound levels exceeded the ERM in two subregions. Average levels of copper exceeded the ERM in six subregions and upper ranges exceeded the ERM in six additional regions (figure 28).

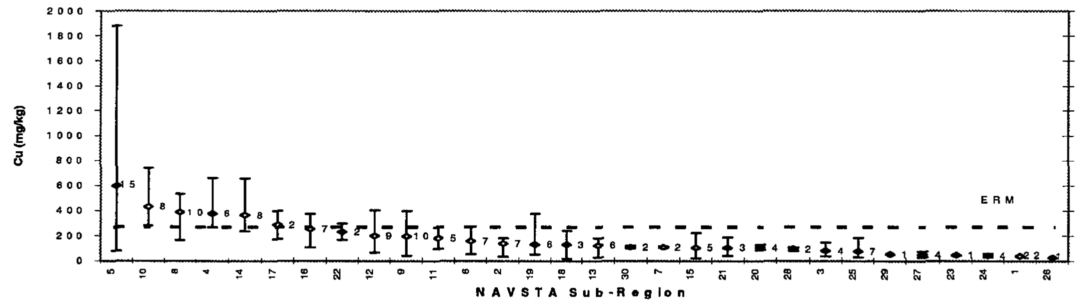

Figure 28. Ranking of subregion average copper concentrations. Bars indicate the lower and upper range of observations within the subregion, and the number next to the symbol indicates the number of observations in the subregion. Figure 26 shows subregion locations.

The copper plot is shown as an example, however, all chemicals were examined in a similar manner. For mercury, average concentrations exceeded the ERM in five regions and the upper range of mercury levels exceeded the ERM in another 10 subregions. Data for PAHs and PCBs were somewhat limited so that some subregions had insufficient data to establish ranges. No average PAH concentrations exceeded the ERM and the upper range exceeded the ERM in three regions. For PCBs, average levels exceeded the ERM in four subregions, while five additional subregions had upper ranges that exceeded the ERM. Lead had no average levels exceeding the ERM; however, upper bound levels in two regions did exceed the ERM. Average levels of zinc exceeded the ERM in five subregions and the upper range exceeded the ERM in four additional subregions. These results suggest that of the subgroup of chemicals studied in detail, copper, mercury, PCBs, and zinc are the most important in terms of spatial extent of elevated levels.

Chemical and biological characteristics in each of the subregions within the NAVSTA piers were examined in detail. The subregions which lie within the NAVSTA pier area include numbers 1, 2, and 6 through 17 (see figure 26). Results that are summarized below represent chemistry exceedences of ERMs and are not based on the relative rankings discussed above.

Subregion 1

Subregion 1 includes the channel area that leads into the mouth of Chollas Creek. Sediments within this area are comparatively sandy and uncontaminated. Although Chollas Creek is a significant source of contamination (see section 6.2.1), much of the material deposited at the mouth of the creek is coarse, while the finer materials which tend to carry the chemicals appear to be carried further out into the bay. No chemicals within Subregion 1 had average levels above the ERM; however, mercury and zinc did have upper range levels above the ERM. Amongst the subregions in the overall NAVSTA area, these sediments generally ranked among the lowest in terms of average chemical concentrations with the exception of PAHs and lead, chemicals that are commonly associated with runoff. Only two PAH and two PCB measurements were available in this subregion, while the remainder of the chemicals had at least 20 measurements. The average overall incidence of exceedence of the ERM in this subregion was 2 percent.

Figure 25 indicates that most measurements in Subregion 1 were for chemistry. One site was studied for biological effect where five separate tests were performed. Of these, effects were observed in three tests and no effects in two. Tests that showed effects included *C. gigas* survival, P450 induction, and the OSI index. Tests that showed no effects included *R. abronius* survival and *C. gigas* development. Note that the survival and development results were from different tests and species reacted differently. The overall incidence of biological effects in this subregion was 60 percent. The limited data in this subregion may suggest a need for additional biological effect studies.

Subregion 2

Subregion 2 includes the region near the mouth of Paleta Creek and is bordered on the south by the Mole Pier. Chemical levels in the region were generally among the upper half of the subregion ranking, and levels of cadmium, mercury, PAHs, PCBs, lead, and zinc ranked among the top five of the subregions evaluated. Chemicals in this region with average levels exceeding the ERM included mercury, PCBs, and zinc. Relatively low levels of copper in this subregion are presumably due to the absence of major ship berthing and ship repair activities. Four PAH samples were available in this subregion and the remaining chemicals had at least six measurements. The average overall incidence of exceedence of the ERM in this subregion was 18 percent.

Results from a total of 26 biological effect assays were available in Subregion 2. Of these, 17 showed effects and eight showed no effects. Effects were observed in all tests of *C. gigas* survival, *C. gigas* development, P450 induction, *Gonyaulax sp.* bioluminescence inhibition, *Mysidopsis sp.* survival, *Skeletonema sp.* survival, as well as benthic community index and OSI. Of four survival tests with *R. abronius*, effects were observed in three tests and no effects in one. Effects were observed using *S. purpuratus* for pore water tests at two sites, while no effects were seen at one site. In reference to the benthic community analysis, reduced species evenness was found at one site and no reduction in evenness at three sites. No effects were observed in tests of *Neanthes sp.* survival, *Menidia sp.* survival, or *Haliotis sp.* development. The overall incidence of biological effects in this subregion was 64 percent. Biomarker and bioaccumulation results from present studies indicate potential bioavailability of PAHs.

Subregion 6

Subregion 6 lies within the piers at the northern extent of NAVSTA, just off the mouth of Chollas Creek. Chemical levels in Subregion 6 generally fell in the mid-range of the overall ranking. No chemicals in Subregion 6 had average levels exceeding the ERM, although copper, mercury, and silver had an upper range that exceeded the ERM. Three PAH measurements and five PCB measurements were available in Subregion 6, while the remaining chemicals generally had seven measurements. Characteristics within Subregion 6 appear to be similar to Subregion 1 in Chollas Creek but with somewhat more elevated chemical levels. The average overall incidence of exceedence of the ERM in this subregion was 6 percent.

Results from a total of 18 biological effect assays were available in Subregion 6. Of these, 11 showed effects and 7 showed no effects. Effects were observed at two sites in the benthic community index. Of six survival tests with *R. abronius*, effects were observed in three tests, and no effects were seen in the other three. Effects were observed using *S. purpuratus* for pore water tests at five sites, while one site showed no effects. Effects were observed in one test of survival for *G. japonica* and no effects in one other. No effects were observed in two tests of *Haliotis sp.* development. The overall incidence of biological effects in this subregion was 61 percent.

Subregion 7

Subregion 7 lies along the outer portion of the piers at the northern extent at NAVSTA, stretching across to the piers at NASSCO. Data within Subregion 7 were limited. For most

chemicals, only two measurements were available, for PCBs, there was only one measurement, while for mercury, there were eight. In general, chemical levels were somewhat similar to Subregion 6, with only mercury having an upper range that exceeded the ERM. The average concentration for lead recorded in this region was the second highest among all subregions at near 125 $mg \cdot kg^{-1}$, a level approaching, but below the ERM. The average overall incidence of exceedence of the ERM in this subregion was 2 percent.

Results from a total of 10 biological effect assays were available in Subregion 7. Of these, seven showed effects and three showed no effects. Effects were observed in all tests of *C. gigas* survival and *R. abronius* survival. Of five survival tests with *G. japonica*, four showed effects and one showed no effects. No effects were observed in *C. gigas* development or the OSI. The overall incidence of biological effects in this subregion was 70 percent.

Subregion 8

Subregion 8 lies along the inner portion of the ship berthing area between Piers 2 through 5 at NAVSTA. Sediments in this area near the quay wall were characterized by high TOC and fines content. Chemical levels within this subregion ranked among the upper three of all subregions for every chemical. For lead, cadmium, silver, and PCBs, Subregion 6 had the highest average levels of all subregions. Average levels of silver, copper, mercury, PCBs, and zinc within the region all exceeded their respective ERMs. The number of measurements in Subregion 6 generally exceeded four. The average incidence of exceedence of the ERM in this subregion was 50 percent.

Results from a total of 28 biological effect assays were available in Subregion 8. Of these, 16 showed effects and 12 showed no effects. Effects were observed in all tests of *C. gigas* survival, *R. abronius* survival, *S. purpuratus* development, and P450 induction. Of 16 survival tests with *G. japonica,* 10 showed effects and six showed no effects. One site showed effects in the benthic community index, and one showed no effects. No effects were observed in *C. gigas* development, *Gonyaulax sp.* bioluminescence inhibition, *Mysidopsis sp.* survival, *Skeletonema sp.* survival, or *Menidia sp.* survival. The overall incidence of biological effects in this subregion was 67 percent.

Subregion 9

Subregion 9 falls along the outer portion of the piers between Piers 2 through 5 at NAVSTA. Chemical levels in this region ranked from moderate to high relative to other regions, with levels of cadmium, mercury, silver, PAHs, PCBs, and zinc ranking among the top five of all subregions. Average levels of mercury, PCBs, and zinc exceeded the ERM, as did the upper range levels of copper, lead, and PAH. Chemicals present in this subregion are similar to those in the adjacent Subregion 8 but are at somewhat lower levels. The number of measurements within the region generally exceeded eight with the exception of PAHs, for which there were only six. The average overall incidence of exceedence of the ERM in this subregion was 22 percent.

Results from a total of 39 biological effect assays were available in Subregion 9. Of these, 16 showed effects and 23 showed no effects. Effects were observed in all tests of *C. gigas* survival, P450 induction, benthic community index, and OSI. Of 17 survival tests with *G. japonica*, effects were observed in six tests and no effects were observed in 10. One site showed effects in *S. purpuratus* development, and two showed no effects. Effects were ob-

served on *R. abronius* at two sites and no effects were observed at two other sites. No effects were observed in *C. gigas* development, *Neanthes sp.* survival, *Gonyaulax sp.* bioluminescence inhibition, *Mysidopsis sp.* survival, *Skeletonema sp.* survival, *Menidia sp.* survival, or *Haliotis sp.* development. The overall incidence of biological effects in this subregion was 46 percent.

Subregion 10

Subregion 10 is located along the quay wall between Piers 5 through 7 at NAVSTA. Chemical levels in Subregion 10 ranked from moderate to high compared to other regions, with levels of cadmium, copper, mercury, and silver ranking among the top five of all subregions. Average levels of copper and mercury exceeded the ERM, as well as the upper range levels of cadmium, PCBs, and zinc. The number of measurements within the subregion generally exceeded eight with the exception of PCBs and PAHs. The average overall incidence of exceedence of the ERM in this subregion was 25 percent.

Results from a total of 30 biological effect assays were available in Subregion 10. Of these, 20 showed effects and 10 showed no effects. Effects were observed in all tests of benthic community index. Of eight survival tests with *G. japonica*, seven showed effects and one showed no effects. Two sites showed effects in *S. purpuratus* development, and one showed no effects. Effects were observed using *R. abronius* at four sites and no effects were observed at two other sites. Effects on the survival of *Neanthes sp.* were observed at one site and no effects at three sites. No effects were observed in *C. gigas* development or *Haliotis sp.* development. The overall incidence of biological effects in this subregion was 67 percent.

Subregion 11

Subregion 11 lies along the outer portion of the piers between Piers 5 through 7 at NAVSTA. Chemical levels in Subregion 11 ranked in the mid-range compared to other regions. Average levels of all chemicals were below the ERM, while the upper range level of mercury exceeded the ERM. The average overall incidence of exceedence of the ERM in this subregion was 4 percent.

Results from a total of 20 biological effect assays were available in Subregion 11. Of these, 14 showed effects and six showed no effects. Effects were observed in all tests of *R. abronias* survival, benthic community index, and OSI. Of eight survival tests with *G. japonica,* four showed effects and four showed no effects. Two sites showed effects in *S. purpuratus* development, and one showed no effects. The overall incidence of biological effects in this subregion was 70 percent.

Subregion 12

Subregion 12 is located along the quay wall between Pier 7 and the Mole Pier at NAVSTA. The southern portion of Subregion 12 lies adjacent to the mouth of Paleta Creek. Chemical levels in Subregion 12 ranked in the mid-range compared to other regions, with the exception of cadmium, which ranked fourth highest among all subregions. Average levels of all chemicals were below the ERM, while the upper range levels of cadmium, copper, zinc and PCBs exceeded the ERM. Six measurements were available for PAHs in Subregion 12, while the number of measurements of other chemicals ranged from 8 to 11. The average overall incidence of exceedence of the ERM in this subregion was 6 percent.

Results from a total of 19 biological effect assays were available in Subregion 12. Of these, five showed effects and 14 showed no effects. Effects were observed in all tests of *S. purpuratus* and benthic community index. Of three survival tests with *G. japonica*, two showed effects and one showed no effects. One observation showed effects in *S. purpuratus* development, and three showed no effects. No effects were observed in *Neanthes sp.* survival, species evenness index or OSI. The overall incidence of biological effects in this subregion was 26 percent.

Subregion 13

Subregion 13 is located along the outer portion of the piers between Pier 7 and the Mole Pier at NAVSTA. Chemical levels in Subregion 10 ranked in the mid-range compared to other regions, with the exception of PAH levels that ranked second highest among all subregions. Average levels of all chemicals were below the ERM; however, the upper range of PAHs and PCBs exceeded the ERM. The number of measurements for chemicals within the subregion ranged from five to six. The average overall incidence of exceedence of the ERM in this subregion was 8 percent.

Results from a total of 19 biological effect assays were available in Subregion 13. Of these, six showed effects and 13 showed no effects. Effects were observed in all tests of benthic community index. Of three survival tests with *G. japonica*, two showed effects and one showed no effects. One observation showed effects in *S. purpuratus* development, and one showed no effects. Effects on *R. abronius* survival were observed at one site while three sites showed no effects. The OSI showed effects in one observation and no effects in one other observation within the subregion. No effects were observed in *Neanthes sp.* survival, P450 induction, *C. gigas* development, *C. gigas* survival or species evenness index. The overall incidence of biological effects in this subregion was 32 percent.

Subregion 14

Subregion 14 is located along the quay wall between the Mole Pier and Pier 13 at NAVSTA. Chemical levels in Subregion 10 ranked from moderate to somewhat high compared to other regions, with levels of copper ranking fifth highest among all subregions. The number of measurements for chemicals within the subregion ranged from 8 to 20. Average levels of copper, and upper bound levels of mercury, PCBs, and zinc exceeded the ERM. The average overall incidence of exceedence of the ERM in this subregion was 19 percent.

Results from a total of 22 biological effect assays were available in Subregion 14. Of these, 14 showed effects and eight showed no effects. Effects were observed in all tests of *S. purpuratus* and P450 induction. Of 12 survival tests with *G. japonica*, nine showed effects and three showed no effects. Effects on *R. abronius* survival were observed at two sites while one site showed no effects. No effects were observed in *Neanthes sp.* survival, *C. gigas* development, *C. gigas* survival, or OSI. The overall incidence of biological effects in this subregion was 64 percent.

Subregion 15

Subregion 15 is located along the outer portion of the piers between the Mole Pier and Pier 13 at NAVSTA. Chemical levels in Subregion 15 ranked in the mid-range compared to other regions. The number of measurements for chemicals within the subregion ranged from three for PCBs to 20 for mercury. Average levels of all chemicals were below the ERM, and only

the upper range level of mercury exceeded the ERM. The average incidence of exceedence of the ERM in this subregion was 5 percent.

Results from a total of 22 biological effect assays were available in Subregion 15. Of these, nine showed effects and 13 showed no effects. Effects were observed in all tests of P450 induction. Of 14 survival tests with *G. japonica,* six showed effects and eight showed no effects. Effects on *R. abronius* survival were observed at two sites while one site showed no effects. No effects were observed in *Neanthes sp.* survival, *C. gigas* development, *C. gigas* survival, or OSI. The overall incidence of biological effects in this subregion was 41 percent.

Subregion 16

Subregion 16 is located along the quay wall between Pier 13 and the 24th Street Marine Terminal. The southern portion of the subregion is not considered part of the restricted NAVSTA navigational area and there is no Navy ship berthing in this portion of the subregion. Chemical levels in Subregion 16 ranked in the mid-range compared to other regions. Average levels of all chemicals were below the ERM, while the upper range level of copper exceeded the ERM. High levels of copper in this region have been reported previously in association with a copper ore loading facility at the 24th Street Marine Terminal. Sediment at this site was removed and treated to bring levels down to a threshold concentration of 1000 $mg{\cdot}kg^{-1}$. Although this is still above the ERM, it was believed that copper in the form of ore would not be significantly bioavailable. The number of measurements within the subregion ranged from 4 to 11. The average overall incidence of exceedence of the ERM in this subregion was 5 percent.

Results from a total of 26 biological effect assays were available in Subregion 16. Of these, 16 showed effects and 10 showed no effects. Effects were observed in all tests of P450 induction. Of 14 survival tests with *G. japonica,* six showed effects and eight showed no effects. Effects on *R. abronius* survival were observed at two sites while one site showed no effects. No effects were observed in *Neanthes sp.* survival, *C. gigas* development, *C. gigas* survival, or OSI. The overall incidence of biological effects in this subregion was 62 percent

Subregion 17

Subregion 17 is located along the outer portion of the piers between Pier 13 and the 24th Street Marine Terminal. The southern portion of the subregion is not considered part of the restricted NAVSTA navigational area and there is no Navy ship berthing in this portion of the subregion. Chemical levels in Subregion 16 ranked in the low-range to mid-range compared to other regions, with the exception of copper and mercury, which both ranked sixth highest among all regions. The number of measurements within the subregion ranged from one to seven. Average levels of copper exceeded the ERM while levels of all other chemicals were below the ERM. High levels of copper in this region have been reported previously in association with a copper ore loading facility at the 24th Street Marine Terminal as with Subregion 16. The average overall incidence of exceedence of the ERM in this subregion was 8 percent.

Results from a total of 10 biological effect assays were available in Subregion 17. Of these, five showed effects and five showed no effects. Effects were observed in all tests of *C. gigas* development and P450 induction. Of five survival tests with *G. japonica*, three showed effects and two showed no effects. Effects on *R. abronius* survival were observed at two sites

while one site showed no effects. No effects were observed in *C. gigas* survival, *R. abronius* survival, or OSI. The overall incidence of biological effects in this subregion was 50 percent.

5.4.4 Summary—Spatial Distribution of Sediment Quality

A mapping of subregion classification into three groupings was done to visually display the scales of potentially low, moderate, and high impact described in table 22. The shading indicates the relative scales of sediment quality, taking into account the combined effect of exceedences of ERM and observed biological effects. Figure 29 shows the results.

- In general, highest incidences of elevated chemicals and biological effects occur along the industrialized shorelines of San Diego and National City in Subregions 1 through 17.
- Incidence levels in subregions away from the shoreline and bordering the Silver Strand are typically low.
- Within the NAVSTA pier area, Subregions 8 and 10 would be classified as high-impact, Subregions 1, 2, 6, 7, 9, 11, 14, 16, and 17 would be classified as moderate-impact, and Subregions 12, 13, and 15 would be classified as low-impact.
- Outside the NAVSTA pier area, Subregions 4 and 5 would be classified as high-impact, Subregions 18, 22, 24, and 26 would be classified as moderate-impact, and the remaining subregions would be classified as low-impact.

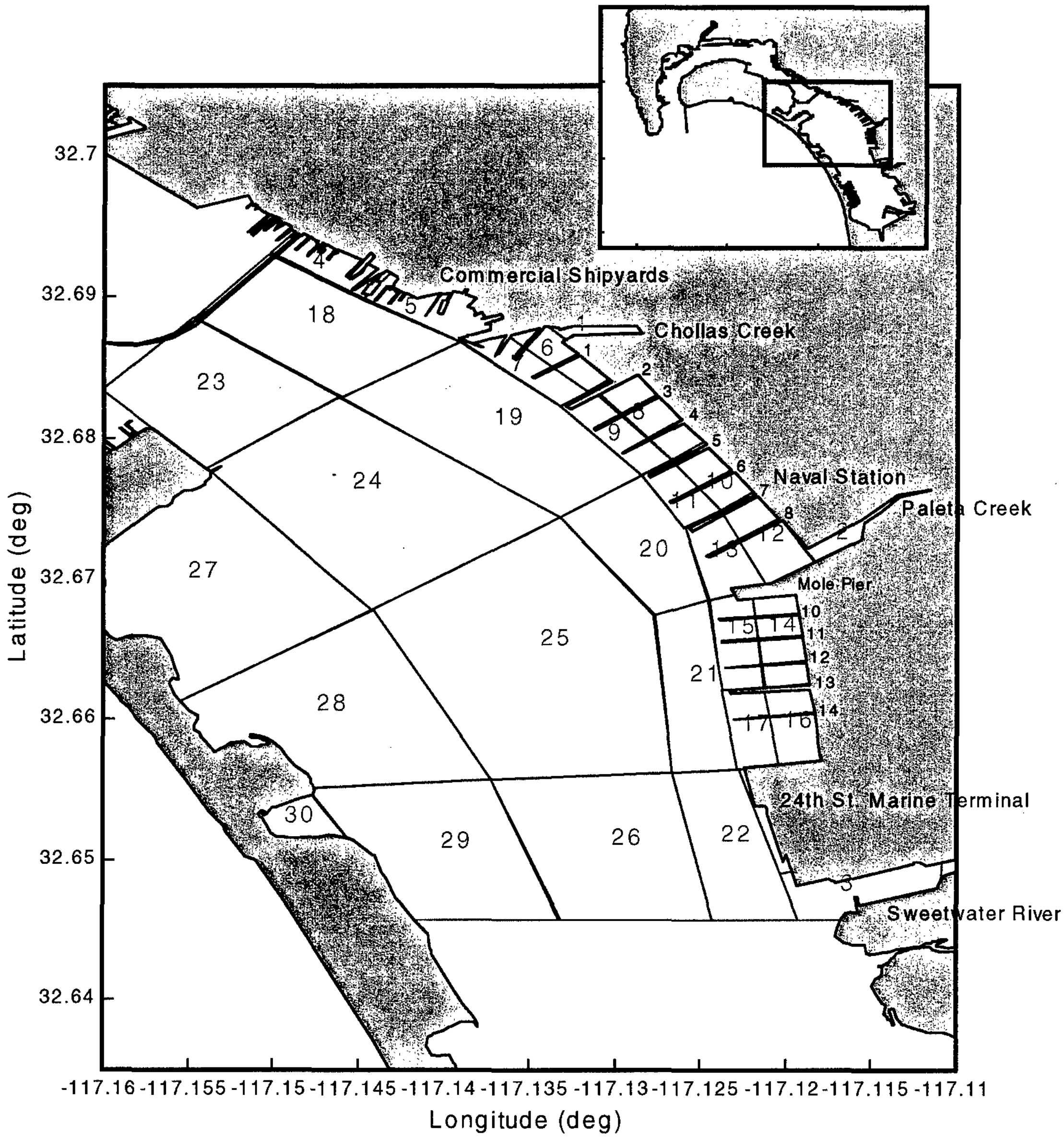

Figure 29. Spatial distribution of sediment quality in the NAVSTA area based on the criteria described in table 22, which takes into account the combined effect of exceedences of ERM and observed biological effects. Dark areas indicate high incidence of elevated chemicals and biological effects. Medium shading indicates areas of moderate combined incidence. Light areas indicate relatively low combined incidence. Shaded areas in this figure correspond to those in figure 27.

6. SEDIMENT PROCESSES

6.1 SOURCE CHARACTERIZATION

San Diego Bay has a notable history of pollutant inputs. For example, a 1951 report to the Regional Board [8] indicated that one of the aircraft manufacturing plants routinely discharged untreated spent plating, anodizing, and some stock solutions into the Bay at a rate of 30,000 gallons per day. Unfortunately, many other industries with pathways to the bay utilized similar disposal methods, along with other commercial, residential, recreational, and military-related discharges. In the subsequent years, many disposal practices such as these were discontinued. In this project, specific studies were carried out to further delineate inputs from storm water and creosote pier pilings. In addition, other sources including antifouling coatings, hull cleaning, spills, cathodic protection, and terrestrial sources were examined primarily from previously published data. Some areas where pollutants were historically utilized or stored in various shoreside activities are discussed in the following subsections.

6.1.1 Regional Stormwater Inflow Study

A regional stormwater inflow study was conducted to provide an assessment of the marine environmental contamination from stormwater runoff entering the NAVSTA region. Although some monitoring has taken place in San Diego Bay, there is a significant lack of information regarding several potential sources into the Bay including non-point runoff, streams, and rivers. Quantification of chemical loading from two major stormwater sources to San Diego Bay in the NAVSTA area, Paleta Creek, and Sweetwater River, was undertaken. Toxicity was also evaluated on stormwater samples collected from Paleta Creek and Sweetwater River (upstream of NAVSTA) during the 1995/1996 storm season with identical sampling gear to that employed by the San Diego and Co-Permittee stormwater monitoring program [18].

Methods. Paleta Creek and Sweetwater River inputs to San Diego Bay were monitored during the winter of 1995/1996, the spring of 1996, and again in the winter of 1996/1997 to determine the volume of stormwater input and pollutant loading to San Diego Bay from these sources. Both monitoring sites were located inland of naval facilities that border San Diego Bay. They were selected to be above the influence of tidal effects and in areas that provided the most favorable hydraulic characteristics for measurement of flow rates.

Three stormwater events were monitored at each site and samples were collected in a flow-proportional manner so that mass-loading estimates could be developed. Physical, chemical, and biological characterization was performed on the composite samples collected. Samples were analyzed for chemicals of concern including five trace metals (copper, lead, silver, zinc, and mercury), TPH as diesel, PAHs, PCBs, and total suspended solids (TSS). For the bioassay tests, the samples were adjusted to seawater salinity using artificial sea salts, and nutrients were added as well. Toxicity was examined for the chain diatom, *Skeletonema costatum,* which was tested for 96 hours in static conditions.

Additionally, watershed characteristics and land-use patterns were developed for each of the two drainages. A simple watershed-model compared measured concentrations and loads

with the expected range of values for each watershed. The model included estimates of discharges from a third watershed that is currently monitored under the City and County of San Diego stormwater monitoring program, allowing result comparisons to previous monitoring at other sites in San Diego Bay. Figure 30 shows the positions of the two watersheds monitored in this study along with a third watershed, Switzer Creek, which was included in the modeling.

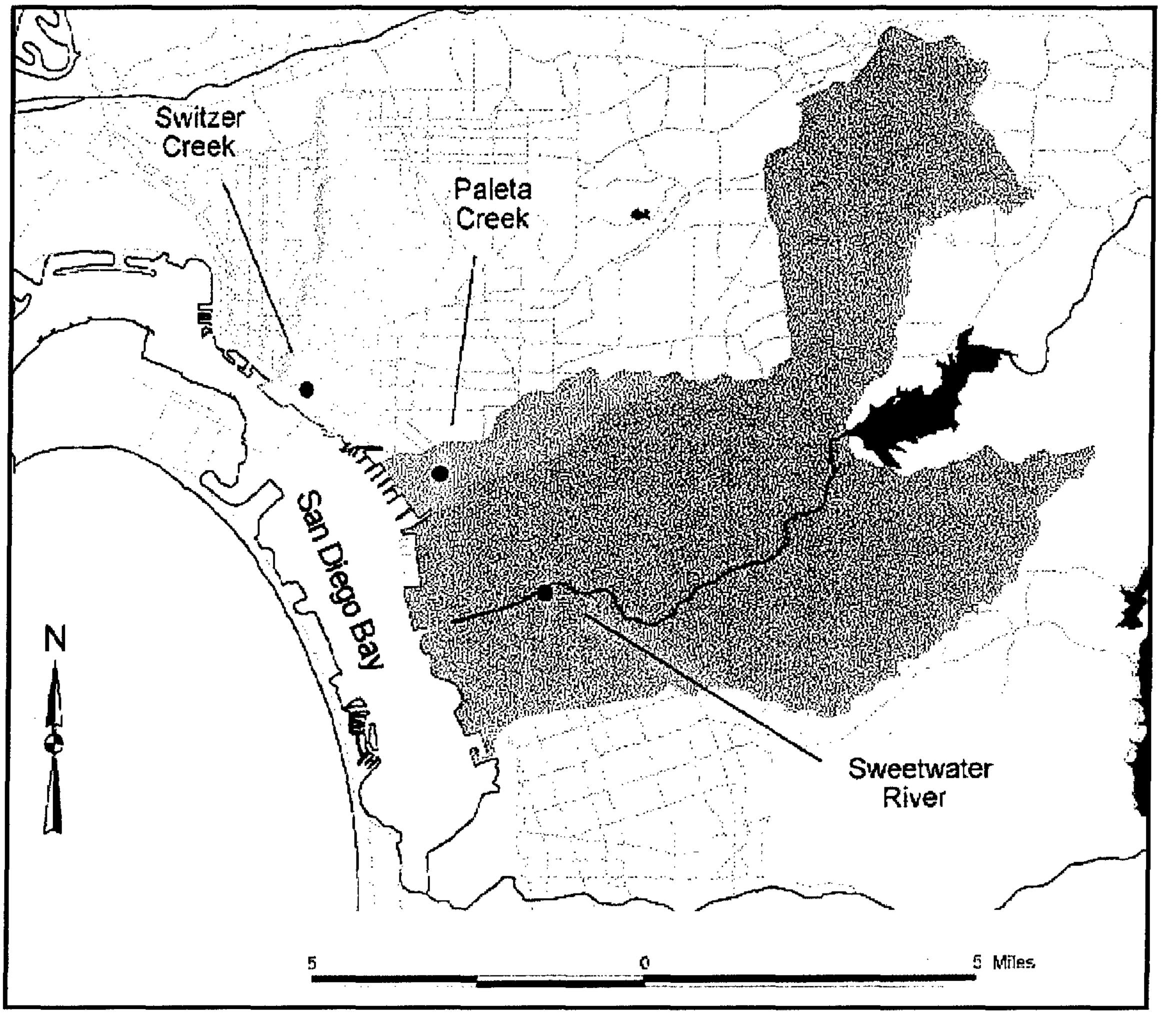

Figure 30. Location of monitoring stations and associated watersheds.

Results. Study results are based upon monitoring three events at each site and on watershed-model projections for pollutant concentrations and loads. These data provided some of the only existing measurements of stormwater runoff from these drainages. Data obtained during this study provided valuable insight regarding pollutant concentrations and loads in stormwater runoff from the Paleta Creek and Sweetwater River watersheds. Although limited to three storm events at each site, the data did allow comparison with watershed-model projections of concentrations and loads for trace metals. The data also provided the first measurements of PAHs, chlorinated hydrocarbons, and PCBs using low-level detection limits. These

data are shown in tables 23 through 28, indicating the event mean concentrations (EMCs) and loading estimates for all chemicals monitored in the watersheds. The sections preceding the tables summarize the findings of the study based upon sampling within each watershed.

Paleta Creek. Copper, lead, and zinc concentrations measured in runoff from the Paleta Creek watershed were consistent with measured concentrations in other mixed land-use drainages in the San Diego area. Mercury and silver were measured in the runoff at concentrations below detection limits used by other studies of stormwater runoff in San Diego so no comparison is possible. Cadmium was only measured in runoff from Paleta Creek during the third event and was consistent with the ranges reported in other urban areas of San Diego.

TSS concentrations were comparable to levels previously measured at other sites that receive runoff from larger drainages with mixed land-use activities. In two of the three events, measured levels exceeded the upper 90th percentile ranges of the watershed-model. This indicates that input parameters used for TSS in the model are not accurately reflecting conditions in Paleta Creek.

The relative abundance of individual PAH compounds in runoff from Paleta Creek was similar in samples from both monitored events. Five of the 23 compounds contributed nearly 60 percent of the total PAH concentration. These included one three-ring PAH (phenanthrene) and four four-ring PAHs (fluoranthene, pyrene, chrysene, and benzo(b) fluoranthene). Concentrations and relative proportions of fluoranthene, pyrene, benzo(e)pyrene, and benzo(a)pyrene were similar to values reported in other urban areas where a relationship was identified to relative proportions of these constituents in used motor oil. This suggests that the source may be from road runoff or motor oil disposal.

Measured concentrations of trace metals (copper, lead, and zinc) and PAHs were within the range of concentrations predicted by the watershed-model. Total PAHs were within watershed-model ranges for the first two events but were about 1/3 of the lower 10th percentile estimates during the third event. The low values recorded during the third event were attributed to a large storm event several days prior to this event. Runoff from Paleta Creek was found to contain low levels of several chlorinated pesticides and PCBs during the final storm event. This was the only event at this site that included these analyses. No toxicity was observed using *Skeletonema costatum* tested for 96 hours in static conditions.

Sweetwater River. Copper, lead, zinc, and cadmium measured in runoff from the Sweet water River watershed were much lower than measured concentrations in other mixed land-use drainages in the San Diego area. Copper, lead, and zinc concentrations were measured below the lower 10th percentile estimates for all three events. Cadmium was not detected (MDL=0.2 $\mu g \cdot L^{-1}$) in runoff from the two events where analyses were conducted for this metal. Mercury and silver were measured in the runoff at concentrations below detection limits used by other studies of stormwater runoff in San Diego, thus no comparison to previous results is possible.

As also noted for Paleta Creek, TSS concentrations were comparable to levels previously measured at other sites that receive runoff from larger drainages with mixed land-use activities but have consistently exceeded the expected ranges of the watershed-model. This indicates that input parameters used for TSS in the watershed-model are not accurately reflecting conditions in San Diego County.

Measured concentrations of all PAH compounds in runoff from the Sweetwater River were extremely low. Naphthalene, a low-molecular-weight PAH, was the most abundant PAH compound but was still present at lower levels than recorded during either event at Paleta Creek. Measured concentrations of trace metals (copper, lead, zinc, and cadmium) and PAHs were typically below or near the lower range of concentrations predicted by the watershed-model. Chlorinated hydrocarbons were below detection limits during both events where these compounds were analyzed. Minimal quantities of PCBs were detected. Only two chlorinated biphenyls were detected in runoff from one of the two events. No toxicity was observed using *Skeletonema costatum* tested for 96 hours in static conditions.

Table 23. Summary of 1996–97 stormwater monitoring results from the Paleta Creek watershed.

Analyte	Event 1 (31 Jan–1 Feb 96)		Event 2 (18 Apr 96)		Event 3 (9–12 Dec 96)	
	EMC	Qual.	EMC	Qual.	EMC	Qual.
Trace Metals ($\mu g \cdot L^{-1}$)						
Cadmium	-		-		0.81	
Copper	49		55		27	
Lead	79		54		36	
Mercury	0.005		0.053		0.034	
Silver	0.078		<0.005	ND	0.024	
Zinc	410		440		200	
Conventionals						
TSS ($mg \cdot L^{-1}$)	610		560		230	
TPH-Diesel ($\mu g \cdot L^{-1}$)	180		620		470	
PAHs ($ng \cdot L^{-1}$)						
Naphthalene	204.1		53.8		10	J
Acenaphthylene	16.6	J	12.3	J	3.4	J
Acenaphthene	39.4		43.5		5	J
Fluorene	49.9		39.4			ND
Phenanthrene	657.9		357.3		8.2	J
Anthracene	44.1		41.2		32	
Dibenzothiophene	49.6		33.4		28	
Fluoranthene	1063.9		608.5		63	
Pyrene	1053.2		513.6		78	
Benz(a)anthracene	291.1		178.6		24	J
Chrysene	838.0		405.3		58	
Benzo(b)fluoranthene	649.2		371.4		40	
Benzo(k)fluoranthene	247.3		124.2		19	J
Benzo(e)pyrene	438.9		197.4		33	
Benzo(a)pyrene	337.5		209.5		23	J
Perylene	110.5		87.4		17	
Indeno(1,2,3,-cd)pyrene	273.0		180.1		26	
Dibenzo(a,h)anthracene	68.6		46.9		12	J
Benzo(g,h,i)perylene	391.4		238.2		52	
2-Methylnaphthalene	109.9		46.2		11	J
1-Methylnaphthalene	2.7		37.0		9.3	J
2,6-Dimethylnaphthalene	101.6		62.2		8.4	J
1,6,7-Trimethylnaphthalene	122.6		93.1		14	J
1-Methylphenanthrene	141.2		72.0		12	J
TOTAL PAHs	7,302		4,052		592	

Note: EMC = event mean concentration, Qual = Qualifier, ND = Not Detected, J = estimated value, below reporting limits.

Table 24. Chlorinated pesticides and PCBs measured in stormwater runoff from the Paleta Creek and Sweetwater River watersheds.

Analyte	Event 3 (9–12 Dec 96)		Event 4 (12–13 Jan 97)		Event 5 (23–24 Jan 97)	
	Paleta Creek		Sweetwater River		Sweetwater River	
Chlorinated Pesticides and PCBs ($ng \cdot L^{-1}$)	**EMC**	**Qual.**	**EMC**	**Qual.**	**EMC**	**Qual.**
Aldrin		ND		ND		ND
alpha-BHC	12			ND		ND
beta-BHC	6.5			ND		ND
delta-BHC		ND		ND		ND
gamma-BHC	12			ND		ND
cis-Chlordane	3.9	J		ND		ND
gamma-Chlordane	2.4	J		ND		ND
2,4'-DDD	0.25	J		ND		ND
2,4'-DDE		ND		ND		ND
2,4'-DDT		ND		ND		ND
4,4'-DDD	7.2			ND		ND
4,4'-DDE	7.7			ND		ND
4,4'-DDT		ND		ND		ND
Dieldrin		ND		ND		ND
Endosulfan I		ND		ND		ND
Endosulfan II		ND		ND		ND
Endosulfan Sulfate		ND		ND		ND
Endrin		ND		ND		ND
Endrin Aldehyde	0.012	J		ND		ND
Endrin Ketone	14			ND		ND
Hexachlorobenzene	1.3	J		ND		ND
8 - 2,4'-Dichlorobiphenyl	22		6			ND
18 - 2,2',5-Trichlorobiphenyl	23			ND		ND
28 - 2,4,4'-Trichlorobiphenyl		ND		ND		ND
44 - 2,2',3,5'-Tetrachlorobiphenyl		ND		ND		ND
52 - 2,2',5,5'-Tetrachlorobiphenyl		ND		ND		ND
66 - 2,3',4,4'-Tetrachlorobiphenyl		ND		ND		ND
101 - 2,2',4,5,5'-Pentachlorobiphenyl		ND		ND		ND
105 - 2,3,3',4,4'-Pentachlorobiphenyl		ND		ND		ND
118 - 2,3,4,4',5-Pentachlorobiphenyl	2.6	J		ND		ND
128 - 2,2',3,3',4,4'-Hexachlorobiphenyl		ND		ND		ND
138 - 2,2,3,4,4',5'-Hexachlorobiphenyl		ND		ND		ND
153 - 2,2',4,4',5,5'-Hexachlorobiphenyl		ND		ND		ND
170 - 2,2',3,3',4,4',5-Heptachlorobiphenyl	2	J		ND		ND
180 - 2,2,3,4,4',5,5'-Heptachlorobiphenyl	4.8	J		ND		ND
187 - 2,2',3,4',5,5',6-Heptachlorobiphenyl	0.97	J		ND		ND
195 - 2,2',3,3',4,4',5,6-Octachlorobiphenyl		ND		ND		ND
206 - 2,2',3,3',4,4',5,5',6-Nonachlorobiphenyl	3.6	J	2.6	J		ND
209 - Decachlorobiphenyl		ND		ND		ND

Note: EMC = event mean concentration, Qual. = Qualifier, ND = Not Detected, J = estimated value, below reporting limits

Table 25. Load estimates (in pounds) for trace metals, conventional pollutants and PAHs in discharges from the Paleta Creek watershed during monitored events.

	Event 1 (31 Jan–1 Feb 1996)	Event 2 (18 Apr 1996)	Event 3 (9–12 Dec 1996)
Analyte	**(pounds)**	**(pounds)**	**(pounds)**
Trace Metals			
Cadmium	-	-	0.014
Copper	23.1	20.1	4.6
Lead	37.2	19.7	6.1
Mercury	0.002	0.019	0.006
Silver	0.037	<0.002	0.004
Zinc	193	161	33.8
Conventionals			
TSS	287,200	204,500	38,905
TPH-Diesel	84.8	226	79.5
PAHs			
Naphthalene	0.096	0.020	0.002
Acenaphthylene	0.008	0.005	0.001
Acenaphthene	0.019	0.016	0.001
Fluorene	0.023	0.014	
Phenanthrene	0.310	0.130	0.001
Anthracene	0.021	0.015	0.005
Dibenzothiophene	0.023	0.012	0.005
Fluoranthene	0.501	0.222	0.011
Pyrene	0.496	0.188	0.013
Benz(a)anthracene	0.137	0.065	0.004
Chrysene	0.395	0.148	0.010
Benzo(b)fluoranthene	0.306	0.136	0.007
Benzo(k)fluoranthene	0.116	0.045	0.003
Benzo(e)pyrene	0.207	0.072	0.006
Benzo(a)pyrene	0.159	0.076	0.004
Perylene	0.052	0.032	0.003
Indeno(1,2,3,-cd)pyrene	0.129	0.066	0.004
Dibenzo(a,h)anthracene	0.032	0.017	0.002
Benzo(g,h,i)perylene	0.184	0.087	0.009
2-Methylnaphthalene	0.052	0.017	0.002
1-Methylnaphthalene	0.001	0.014	0.002
2,6-Dimethylnaphthalene	0.048	0.023	0.001
1,6,7-Trimethylnaphthalene	0.058	0.034	0.002
1-Methylphenanthrene	0.066	0.026	0.002
TOTAL PAHs	3.44	1.48	0.100

Table 26. Summary of 1996-97 stormwater results from the Sweetwater River watershed.

Analyte	Event 1 (31 Jan–1 Feb 1996)		Event 4 (12–13 Jan 1997)		Event 5 (23–24 Jan 1997)	
	EMC	Qual.	EMC	Qual.	EMC	Qual.
Trace Metals ($\mu g \cdot L^{-1}$)						
Cadmium	-		<0.2	ND	<0.2	ND
Copper	6.8		4.8		3.8	
Lead	6.8		5.6		2.9	
Mercury	0.060		0.0077		<0.005	ND
Silver	0.014		0.063		0.045	
Zinc	37		26		15	
Conventionals						
TSS ($mg \cdot L^{-1}$)	110		110		52	
TPH-Diesel ($\mu g \cdot L^{-1}$)	<1.0	ND	470		280	
PAHs ($ng \cdot L^{-1}$)						
Naphthalene	39.3		9.8	J	3.1	J
Acenaphthylene	2.4	J	1.2	J	1.6	J
Acenaphthene	2.5	J	2.1	J		ND
Fluorene	3.5	J	2.2	J		ND
Phenanthrene	10.6		12	J	4.7	J
Anthracene	1.8	J	3.9	J	2.7	J
Dibenzothiophene	19.1	J	5.9	J	3.8	J
Fluoranthene	21.0		16		5.8	J
Pyrene	5.7		17		7.3	J
Benz(a)anthracene	18.1		4.6	J	2.3	J
Chrysene	15.5		13	J	4.4	J
Benzo(b)fluoranthene	17.5		12	J	4.2	J
Benzo(k)fluoranthene	12.4		4.7	J	1.6	J
Benzo(e)pyrene	8.6	J	9.8	J	3.3	J
Benzo(a)pyrene	3.8	J	5.1	J	1.8	J
Perylene	8.3		2.7	J	1	J
Indeno(1,2,3,-cd)pyrene	3.0	J	6.6	J	2.4	J
Dibenzo(a,h)anthracene	15.1		1.6	J		ND
Benzo(g,h,i)perylene	11.7		10	J	3.8	J
2-Methylnaphthalene	11.2		2.1	J		ND
1-Methylnaphthalene	7.0	J	1.7	J		ND
2,6-Dimethylnaphthalene	5.6	J		ND		ND
1,6,7-	2.4	J		ND		ND
Trimethylnaphthalene		ND		ND		ND
1-Methylphenanthrene						
TOTAL PAHs	248		144		54	

Note: EMC = event mean concentration, Qual. = Qualifier, ND = Not Detected, J = estimated value, below reporting limits

Table 27. Load estimates (in pounds) for trace metals, conventional pollutants and PAHs in discharges from the Sweetwater River watershed during monitored events

Analyte	Event 1 (31 Jan–1 Feb 1996) (pounds)	Event 4 (12–13 Jan 1997) (pounds)	Event 5 (23–24 Jan 1997) (pounds)
Trace Metals			
Cadmium	-	<0.92	<0.10
Copper	15.8	22.0	1.9
Lead	15.8	25.7	1.4
Mercury	0.139	0.035	<0.002
Silver	0.033	0.289	0.022
Zinc	85.9	119	7.4
Conventionals			
TSS	255,400	505,027	25,768
TPH-Diesel	<2.3	2,158	139
PAHs			
Naphthalene	0.091	0.045	0.002
Acenaphthylene	0.006	0.006	0.001
Acenaphthene	0.006	0.010	-
Fluorene	0.008	0.010	-
Phenanthrene	0.025	0.055	0.002
Anthracene	0.004	0.018	0.001
Dibenzothiophene	0.004	0.027	0.002
Fluoranthene	0.044	0.073	0.003
Pyrene	0.049	0.078	0.004
Benz(a)anthracene	0.013	0.021	0.001
Chrysene	0.042	0.060	0.002
Benzo(b)fluoranthene	0.036	0.055	0.002
Benzo(k)fluoranthene	0.041	0.022	0.001
Benzo(e)pyrene	0.029	0.045	0.002
Benzo(a)pyrene	0.020	0.023	0.001
Perylene	0.009	0.012	0.000
Indeno(1,2,3,-cd)pyrene	0.019	0.030	0.001
Dibenzo(a,h)anthracene	0.007	0.007	-
Benzo(g,h,i)perylene	0.035	0.046	0.002
2-Methylnaphthalene	0.027	0.010	-
1-Methylnaphthalene	0.026	0.008	-
2,6-Dimethylnaphthalene	0.016	-	-
1,6,7-Trimethylnaphthalene	0.013	-	-
1-Methylphenanthrene	0.005	-	-
TOTAL PAHs	0.576	0.661	0.027

6.1.2 Pier Piling Leachate Study

Over the last half-century, creosote has been used ubiquitously in the treatment of wood products that are exposed to the natural elements. Its utility in minimizing wood degradation has made it a common treatment in the protection of telephone poles, railroad ties, roadway rails, and in the marine environment for pier pilings. Thirty percent of contaminated sites slated for bioremediation cleanup by the Environmental Protection Agency listed creosote-derived PAH as one, if not the only group of chemicals of concern (EPA, 1993). Its widespread presence on this list is a result of its carcinogenic nature and its historical popularity as a wood preservative. Because of its potential effects in the marine environment (Stegeman et al., 1991), the effect of PAHs on the marine environment has become a growing concern in environmental site investigations.

As part of ongoing Navy environmental monitoring studies, measurements have previously been made of seawater PAHs in San Diego Bay. These measurements, made over a 5-year period, were acquired using a high spatial resolution UV fluorescence mapping technique (Katz and Chadwick, 1993; Chadwick and Salazar, 1991; Lieberman et al., 1989) calibrated to discrete samples analyzed for PAHs with highly sensitive analytical techniques (Katz et al., 1991). These techniques provided data on the relative distribution of 36 individual PAH compounds with a detection limit of less than 10 ng L^{-1}. As such, these data not only provided quantitative information regarding the amounts of PAHs, but also allowed PAH sources to be assessed. The outcome of these studies suggested that there is a chronic source of PAHs to San Diego Bay, seen over tidal, seasonal, and yearly temporal scales. It was also determined that the hydrocarbons were predominantly derived from a pyrogenic (heat producing) source.

There are several possible pyrogenic PAH sources to San Diego Bay including creek and river runoff, non-point source runoff, atmospheric fallout, and creosote impregnated pilings. Because of the chronic nature of the PAH source and limited seasonality of rainfall events, both point and non-point runoff conditions were considered important but unlikely to be a chronic source. Atmospheric fallout, although not well studied in this climate, has in other climates typically been only a minor component of the PAH inputs. The sheer number of creosote pilings in San Diego Bay suggested that this abundant source could potentially be significant.

Methods. In this study, the flux of PAHs from in-place creosote pier pilings were measured using an *in situ* chamber method to determine their mass loading contribution of the PAHs to San Diego Bay. The intent was to determine the flux rate while maintaining the natural conditions of the pier piling and its surroundings as closely as possible. A stainless steel chamber was constructed with the curvature of a "typical" pier piling and fitted with high-density, closed-cell foam to form an almost watertight seal. The flux was then measured by determining the seawater concentration of PAHs in the system as a function of time by analyzing discrete samples taken out of an auxiliary chamber, and by monitoring the UV fluorescence. By placing the chamber onto the piling itself, no new surface area would be exposed, a factor deemed quite important for this study. By flowing seawater through the chamber, it was expected that the natural water circulation conditions would be reasonably simulated. By performing the measurements *in situ*, natural temperature conditions could be maintained. The flux rates thus determined, with estimates of the number of pier pilings in the bay, were then

used to more accurately determine the overall mass loading of PAHs to San Diego Bay from this source.

Results. Three experiments were performed on two separate pilings in San Diego Bay near SSC San Diego facilities on Pt. Loma (Pier 160). Figure 31 shows the results of the three flux experiments. The flux rates measured using the *in situ* method were lower than those measured previously during a laboratory experiment. Our previous laboratory flux estimates made on cut piling pieces ranged from 0.02-0.12 $g \cdot cm^{-2} \cdot yr^{-1}$. Normalizing the *in situ* rates to the enclosed piling surface area of 1445 cm^2 gives fluxes of 0.0022-0.0033 $g \cdot cm^{-2} \cdot yr^{-1}$. Thus, the *in situ* rates are substantially lower than the laboratory rates by a factor of between 6 and 38. This result confirms a previous concern that newly exposed creosote surface area in the laboratory analyses led to unrealistically high flux rates. Furthermore, although these newly measured rates are considerably lower than our previous laboratory analyses, they agree exceptionally well with the laboratory flux measurements of Ingram et al., (1982), who estimated flux rates of 0.0026 $g \cdot cm^{-2} \cdot yr^{-1}$ at seawater temperatures of 20°C. Ingram et al., (1982) also showed that the flux rates have a strong temperature dependence with fluxes increasing twofold to fourfold at seawater temperatures of 30°C.

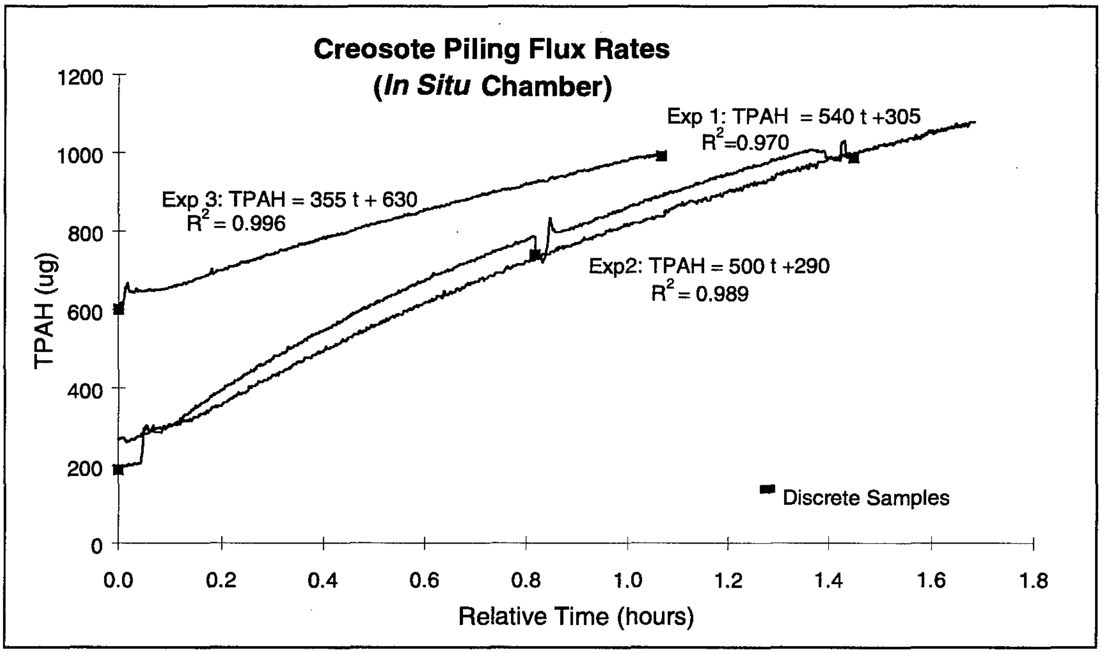

Figure 31. Measured TPAH flux rates from creosote pilings for three in situ flux chamber experiments.

Given estimated PAH flux rates, the total loading of PAH from creosote impregnated pilings to San Diego Bay requires only a determination of the exposed surface area of pilings. A visual count of the number of creosote impregnated pilings was made in June 1995. The total number of creosote pilings in the bay was estimated at 13,600. Up until 1996, 8700 or 64 percent of the pilings were in the back bay, mostly south of the Coronado Bay Bridge, which is an area that has a limited net water exchange. Of the pilings located in the back bay,

the NAVSTA area contained approximately 4460. The mid-bay contained roughly 2300 and the entrance areas contained roughly 2600; both of these areas have relatively higher water exchange than the back bay. Since 1996, approximately 50 percent of the pilings in the back bay have been replaced, leaving approximately 2230 in the NAVSTA region, 4350 in the back bay as a whole, and 9250 in place throughout the bay. Figure 32 shows the general distribution of pilings in the bay. These estimates do not include the hundreds of creosote pilings that are encased in concrete and thus unlikely to have exposed surface area to water leaching. It also did not include the thousands of concrete, copper-treated, untreated, and newly installed plastic pier pilings used throughout the bay. With a flux of 0.0022 to 0.0033 $g \cdot cm^{-2} \cdot yr^{-1}$, the total potential historical input from this source was estimated to be 3.1 to 4.6 $mt \cdot yr^{-1}$. A current estimate of potential input throughout the bay from the remaining creosote pier pilings is 2.1 to 3.1 $mt \cdot yr^{-1}$

Two uncertainties should be acknowledged in these estimates. One unknown factor in this mass loading estimate is the effect of biofouling on the amount of surface area available for flux. In general, the pilings in the bay are highly colonized with biological growth below the high tide level. It is expected that the biofouling reduces the effective surface area available for flux, although it is possible that it can also act to expose new surface area. There is no easy way to estimate the effective surface area, especially when most of the piling surface area is below the water surface. An initial goal of placing the chamber over portions of the piling that were fouled was abandoned as a result of the inability to form a good seal. Another consideration for this loading estimate is the effect of temperature on the flux rate. These measurements were made in the late fall when temperatures averaged about 16°C. However, our monitoring studies suggest a yearly average temperature for the whole bay is roughly 20°C and temperatures reach 29°C in the back portions of the bay during summer. The impact of adjusting the flux rate for average temperature would be to increase the mass loading estimate above. It also suggests a differential flux rate in various parts of the bay. For instance, under summertime conditions, flux rates could certainly be three times higher in the back bay than those found at the entrance.

When compared to the typical distribution of UV fluorescence measured at vertical profiles along an axial transect of the bay (figure 33), it is clear that there is strong correlation between increasing fluorescence, which is directly comparable to TPAH concentration and the number of pier pilings. The higher number of pier pilings together with reduced exchange rates and increasing temperatures in the back bay promotes the likelihood that the higher PAH levels observed in the back bay are derived from the pilings. A comparison of the compositional distribution of PAHs found in bay water with that of a creosote standard and that found in the flux experiment samples is shown in figure 34, with the analytes shown in table 29. With the exception of the naphthalenes and biphenyl, which are the most volatile of the compounds and are lost relatively quickly in the environment, the compositional makeup of the three samples was quite comparable, suggesting similar sources. The high degree of similarity in the compositional makeup along with the strong spatial correlation of pilings and seawater PAH concentrations suggests that the creosote pilings are a significant source of PAH to San Diego Bay.

Conclusions. Conclusions from this study can be summarized as follows. The flux rate of PAHs from creosote pilings using *in situ* methods ranged from 0.0022 to 0.0033 $g \cdot cm^{-2} \cdot yr^{-1}$. The current mass loading of PAHs to San Diego Bay, based on the total available piling surface area, is between 2.1 and 3.1 $mt \cdot yr^{-1}$. The spatial distribution of seawater PAH

concentrations in the bay closely resembles the general distribution of pilings. Additionally, the PAH compositional makeup of the waters in the back bay closely resemble that of a creosote standard and that measured in the flux experiment. The Navy has been mitigating the effects of the creosote pier pilings by removing them and replacing them with plastic ones. Since 1996, 64 percent of the creosote pilings have been removed from the back bay, and this effort is continuing.

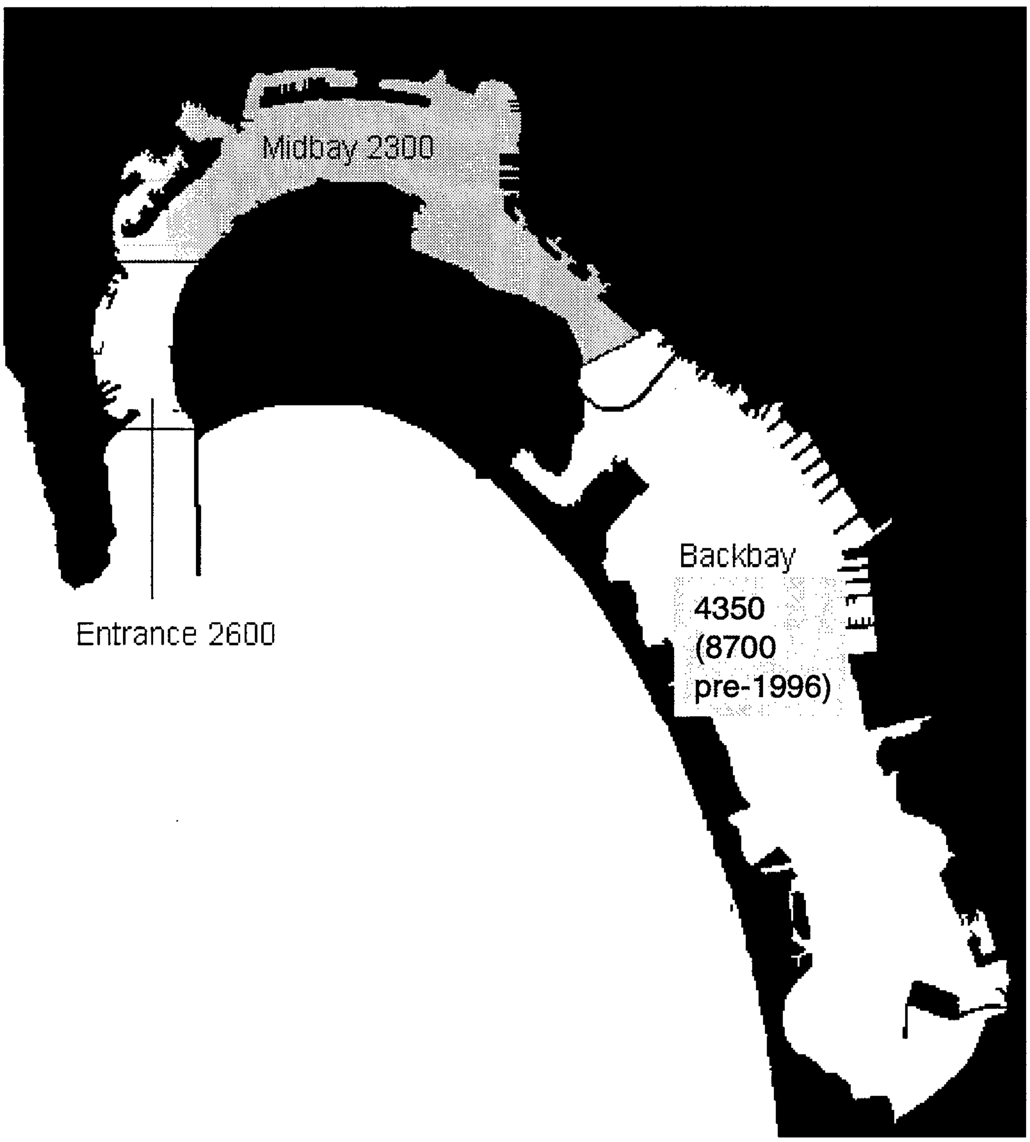

Figure 32. General distribution of creosote pier pilings in San Diego Bay.

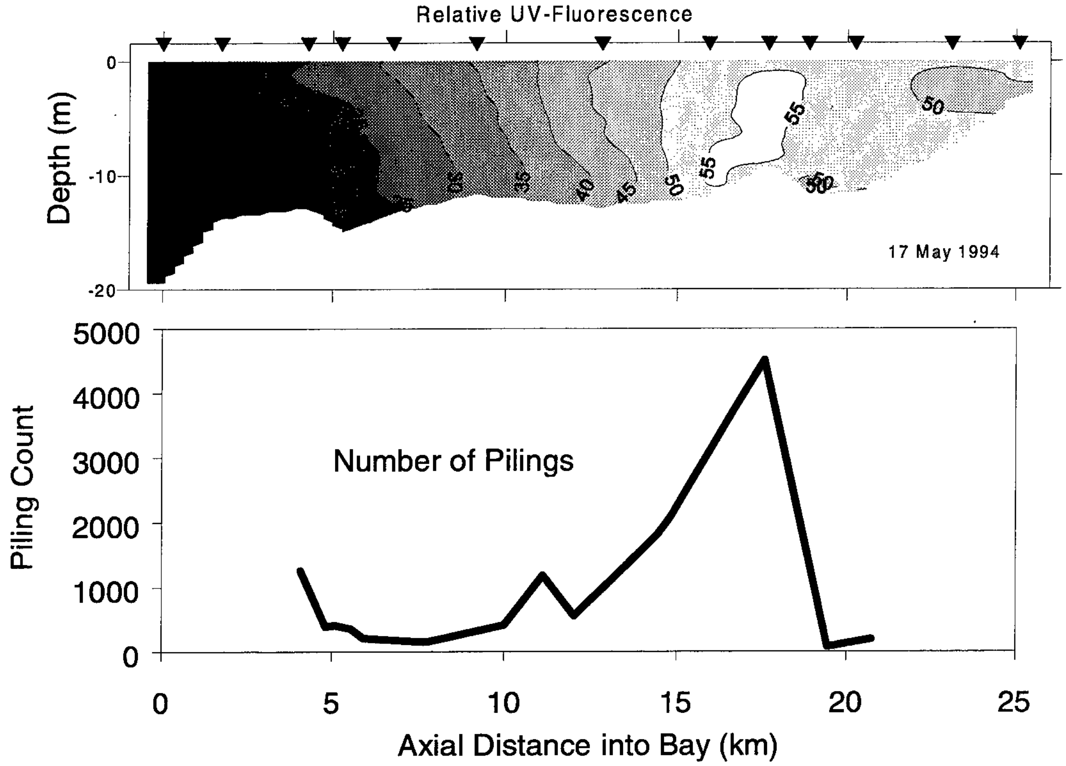

Figure 33. Relative UV fluorescence and number of creosote pier pilings as a function of axial distance into San Diego Bay from the mouth.

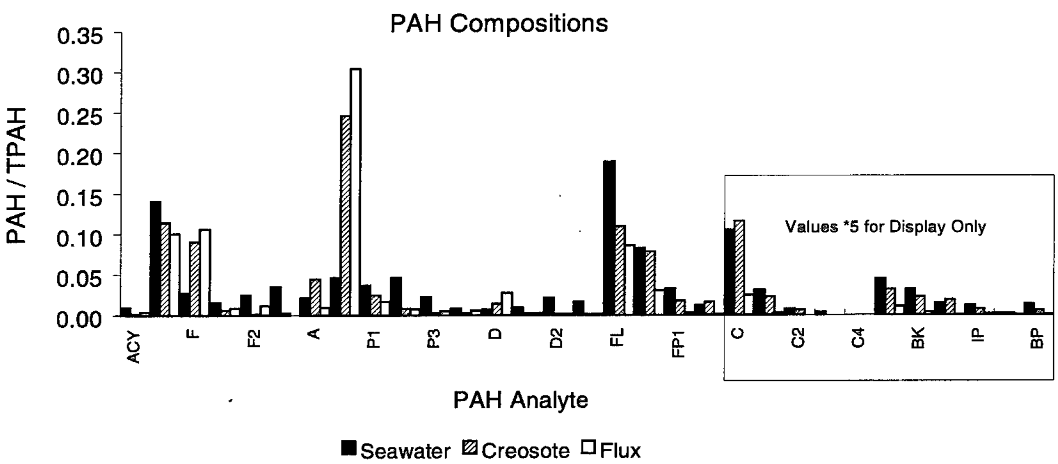

Figure 34. Relative composition of PAH compounds in San Diego Bay seawater, a creosote standard, and in a flux chamber sample. Analytes are in the same order as shown in the table 29.

Table 28. PAH analytes measured in this study. The analyses were made using a modified EPA 8270 gas-chromatography, mass-spectrometry method (Douglas, 1991).

ID	Analyte	ID	Analyte
N	naphthalene	D1	C1-dibenzothiophenes
N1	C1-naphthalenes	D2	C2-dibenzothiophenes
N2	C2-naphthalenes	D3	C3-dibenzothiophenes
N3	C3-naphthalenes	FL	fluoranthene
N4	C4-naphthalenes	PY	pyrene
AC	acenaphthylene	FP1	C1-fluoranthenes/pyrenes
AE	acenaphthene	BA	benzo(a)anthracene
F	fluorene	C	chrysene
F1	C1-fluorenes	C1	C1-chrysene
F2	C2-fluorenes	C2	C2-chrysene
F3	C3-fluorenes	C3	C3-chrysenes
A	anthracene	C4	C4-chrysenes
P	phenanthrene	BB	benzo(b)fluoranthene
P1	C1-phenanthrenes/anthracenes	BK	benzo(k)fluoranthene
P2	C2-phenanthrenes/anthracenes	BAP	benzo(a)pyrene
P3	C3-phenanthrenes/anthracenes	IP	indeno(1,2,3-c,d)pyrene
P4	C4-phenanthrenes/anthracenes	DA	dibenzo(a,h)anthracene
D	Dibenzothiophene	BP	benzo(g,h,i)perylene

6.2 SOURCE BUDGETS

6.2.1 Stormwater Chemical Loading

With the availability of stormwater runoff hydrological and chemical data described in the section on regional stormwater inflows, as well as NPDES stormwater monitoring data, it is possible to estimate some pollutant loading into the bordering NAVSTA region from the Chollas Creek, Paleta Creek, Switzer Creek, and Sweetwater River drainage basins, and from NAVSTA itself (see figure 30). Collectively, these data will further improve estimates of stormwater pollutant loading to the bay, and permit a broader perspec-tive of bay pollutant loading from NAVSTA. Table 30 summarizes the estimated stormwater runoff loading from each of these areas.

As described in the section on regional stormwater inputs, the creek data are presented as even mean concentrations, whereas the NAVSTA samples were collected within the first-hour or half-hour discharge of a storm event. All of the NAVSTA samples taken had at least

72 hours of dry weather prior to sampling. This will lead to more conservative, or overestimated, pollutant levels from the NAVSTA region than from the creeks. In addition, NAVSTA has maintained a contract to clean, store, and appropriately dispose of stormwater effluent solids from storm drains facility-wide since 1995.

6.2.2 Chemical of Concern Loading from All Sources

Individual budgets for chemicals of concern were estimated for all known sources. Table 31 shows the results of this analysis, along with relative percentages of each source input. Only the known measurable sources are listed, although in some cases (e.g., atmospheric deposition) no data were available even though there was probably some source component albeit a small one. Historical inputs vary for each source and are not shown explicitly in the table, with the exception of bilgewater inputs. Past events may have contributed significant inputs of TPAHs to Chollas Creek, Paleta Creek, and the quay wall area.

6.2.3 Summary

Removal of about 50 percent of the creosote pier pilings at NAVSTA has significantly reduced the TPAH loading; however, budget estimates indicate that the input of TPAH to the NAVSTA region is still dominated by that source. This is supported by PAH fingerprinting studies from seawater samples that showed a close match to the fingerprint of creosote standards. The remainder of the creosote pilings is in the process of removal from NAVSTA, and bilgewater discharges have already been discontinued; therefore, the most significant sources of TPAH are controlled. Other less significant sources of PAHs include fuel spills, compensating fuel ballast, and stormwater. Input from spills was higher; however, the input from stormwater contains a relatively higher proportion of heavy molecular weight PAHs when compared to the fuel products that are generally spilled in the bay.

Copper and zinc input to the Bay is dominated by release from antifouling paint and zinc anode usage for cathodic protection by pleasure boats. Navy ship antifouling and anodes contribute a relatively larger amount of these metals to the NAVSTA region. Stormwater runoff is a minor component of copper input, while zinc input from stormwater runoff may be considered important from Chollas and Paleta Creeks, but is still les than the input from zinc anode usage. Use of these metals in the processes of antifouling and cathodic hull protection has been practiced for decades, and is not expected to cease in the near future due to an absence of proven alternatives. The release of these metals into the marine environment is, therefore, expected to continue for some time. However, impressed-current systems may gradually replace zinc anodes on naval vessels and, hence, reduce zinc input to the bay. Lead may also be expected to continue to be released into the marine environment if its input to stormwater runoff originates from urban streets and highways. Mercury, cadmium, and silver have not been identified as important pollutants in stormwater runoff. With respect to mercury presence in marine sediments, historical use in antifouling paints remains a likely input source that has ceased since the early 1970s. Insufficient data exist at this time to develop a detailed budget for PCBs. However, some recent measurements permitted calculation of loading from the Paleta Creek basin. This amounted to less than 0.1 kg, indicating that little PCB loading is occurring from this drainage basin.

Table 29. Annual mass loading of chemicals from various stormwater sources in the NAVSTA region. All values are in kg·yr^{-1}.

	Ag	Cd	Hg	Cu	Pb	Zn	TPAHs (Zero DL)	TPAHs (Half DL)	TPAHs (DL)	TPAHs (No Est. values)	TPCBs	Acreage
Chollas Creek NAVSTA				29 (42)	3.6 (5.3)	130 (180)	2.8 (4.1)	6.0 (8.8)	9.1 (13)	5.6 (8.2)		209
Paleta Creek NAVSTA				58 (83)	15 (21)	130 (180)	4.2 (6.0)	7.7 (11)	11 (16)	5.8 (8.2)		225
Quay Walls Area NAVSTA				21 (30)	9.2 (13)	83 (120)	0.4 (0.5)	5.6 (7.8)	11 (15)	2.4 (3.4)		298
NAVSTA All Areas		0.9 (1.3)		91 (130)	40 (56)	330 (460)	11 (15)	24 (33)	36 (51)	18 (25)		824
Pre-NAVSTA Chollas Creek	0.2 (0.3)	13 (19)	0.2 (0.3)	430 (610)	730 (1000)	2800 (3900)				0.7 (1.0)		16273
Pre-NAVSTA Paleta Creek	0.1 (0.2)	1.2 (1.8)	0.1 (0.1)	140 (190)	180 (260)	720 (1000)				14 (20)	0.09 (0.13)*	1829
Sweetwater River Basin	0.3 (0.4)	9.4	0.6 (0.8)	59 (85)	61 (87)	315 (449)				2.1 (2.9)		21353
Switzer Creek Basin	0.03* (0.04)*	1.8	0.01* (0.02)*	15 (20)	29 (37)	130 (170)				0.03* (0.05*)		2560
Non-NAVSTA All Areas	0.6	25	0.9	640	1000	4000				17		
Overall Total	0.6	26	0.9	740	1040*	4300				35		

NOTES:

1. Loading values adjusted to two significant figures

2. Acreage not reported in significant figures

3. Pre-NAVSTA Chollas Creek data reflect input from total drainage basin

4. Values in parenthesis were calculated using an annual rainfall value of 9.92 inches

5. Values not in parenthesis were calculated using an annual rainfall value of 6.95 inches — due to lack of comparable data, assumptions were made using average grab samples in comparison with composite samples

6. Pre-NAVSTA Chollas Creek and Switzer Creek values calculated using Paleta Creek EMC for Ag, TPAH, and Hg

7. Sweetwater River and Switzer Creek cadmium inputs were modeled (Kinnetics, 1996)

8. Overall total = NAVSTA all areas + non-NAVSTA using 6.95 inches annual rainfall

*9. * value not adjusted to two significant figures*

Table 30. Estimated annual mass loading of chemicals from all known sources in the NAVSTA region. Top row values in bold are the inputs for each source shown in kg·yr^{-1}; the bottom row values in italics are the percentage contributions of each known source.

Sources	TPAHs	Cu	Zn	Pb	Hg	Cd	Ag	PCBs
NAVSTA Stormwater	**18** *1.1%*	**91** *1.2%*	**330** *2.7%*	**40** *3.8%*	**ND**	**0.9** *2.9%*	**ND**	**ND**
Non-NAVSTA Stormwater	**17** *1.1%*	**640** *8.3%*	**3965** *32.3%*	**1000** *95.9%*	**0.9** *100%*	**25.0** *80.4%*	**0.6** *100%*	**0.09** *100%*
Atmospheric Deposition	**39** *2.4%*	**7** *0.1%*	**5** *0.04%*	**3** *0.3%*	**ND**	**ND**	**ND**	**ND**
Creosote Pilings (50% removed)	**1280** *80.1%*							
Compensating Fuel Ballast	**81** *5.1%*							
Oil Spills	**105** *6.6%*							
Bilgewater (historical)	**57** *3.6%*							
Navy Antifouling Paints		**6177** *79.7%*	**1853** *15.1%*					
Pleasure Craft Antifouling Paint		**719** *9.3%*	**ND**					
Navy In-water Hull Cleaning		**116** *1.5%*						
Navy Cathodic Protection			**5681** *46.3%*			**5.2** *16.7%*		
Pleasure Craft Cath. Protection			**425** *3.5%*					
Annual Totals	**1597**	**7750**	**12259**	**1043**	**0.9**	**31.1**	**0.6**	**0.09**

Note: ND indicates no data available or insufficient data due to detection limits; blanks indicate that there is no known chemical input from that source. The NAVSTA stormwater figures are based on first flush samples while the non-NAVSTA figures represent event mean concentration values.

6.3 CONTAMINANT REMOBILIZATION

6.3.1 Sediment-Water Exchange

Contaminants may enter San Diego Bay from many sources, including ships, shoreside facilities, municipal outfalls, spills, and non-point-source runoff. Bay sediments are typically considered a primary sink for these contaminants. However, if previous disposal practices have resulted in high concentrations of chemicals in the sediments, chemicals may flux out of the sediments. In areas where pollution prevention and remediation practices have removed other chemical sources, remaining contaminated sediments may serve as a primary chemical source to the water column.

To determine whether chemicals are moving into, out of, or remaining immobilized within the sediments, a determination of chemical flux must be made. Reactions in surface sediments control chemical pore water gradients, and the direction and magnitude of these gradients control the diffusive flux across the sediment-water interface. These fluxes can be calculated from measure- ments of chemical pore water gradients and sediment physical properties (Berner, 1980). However, in most coastal areas, pore water gradients are very steep and, therefore, difficult to measure. In addition, flux calculations based on pore water gradients only provide the diffusive component of a chemical flux. An additional concern in coastal areas is that biological irrigation by infauna and wave or current induced flushing may provide a larger component of flux through advection of water through the sediments (Rhoads et al., 1977; Huettel and Gust, 1992). To avoid these problems, a direct measurement of chemical flux in coastal areas is often the chosen method to assess chemical mobility across the sediment-water interface (Westerlund et al., 1986; Berelson et al., 1987). This direct measurement can be made with a flux chamber that isolates a volume of seawater over the sediments to quantify chemical flux across the sediment-water interface. For this purpose, the Navy has developed the Benthic Flux Sampling Device (BFSD), a flux chamber designed specifically for measuring chemical fluxes in coastal areas. A complete description of the BFSD design and operation has been discussed previously by Chadwick et al. (1993). This report will therefore consist of only a brief description of the BFSD, followed by discussion of data from the BFSD deployments in San Diego Bay.

Methods. The BFSD was deployed at the six sampling stations from the 1995 study (figure 1). Figure 35 shows the BFSD, which consists of a tripod frame, an open-bottomed chamber, and associated sampling and control equipment. Once on station, the BFSD is lowered into the water until the sediment surface is viewed by the video camera. If the site is clear (free of debris, rocks, organisms, etc.), the BFSD is raised several meters above the bottom and allowed to fall under a controlled descent for a landing. The downward momentum of the BFSD buries the open-bottomed chamber into the sediments to create a seal. At user-defined intervals, discrete water samples are collected from the chamber for later chemical analysis. After the experiment is completed, recovery of the BFSD is initiated with the release of a marker buoy by an acoustic signal. This buoy is attached to a retrieval line that is used to pull the BFSD to the surface. Experimental data are then downloaded from the data acquisition and control unit. Sample bottles are also removed from the chamber for chemical analysis.

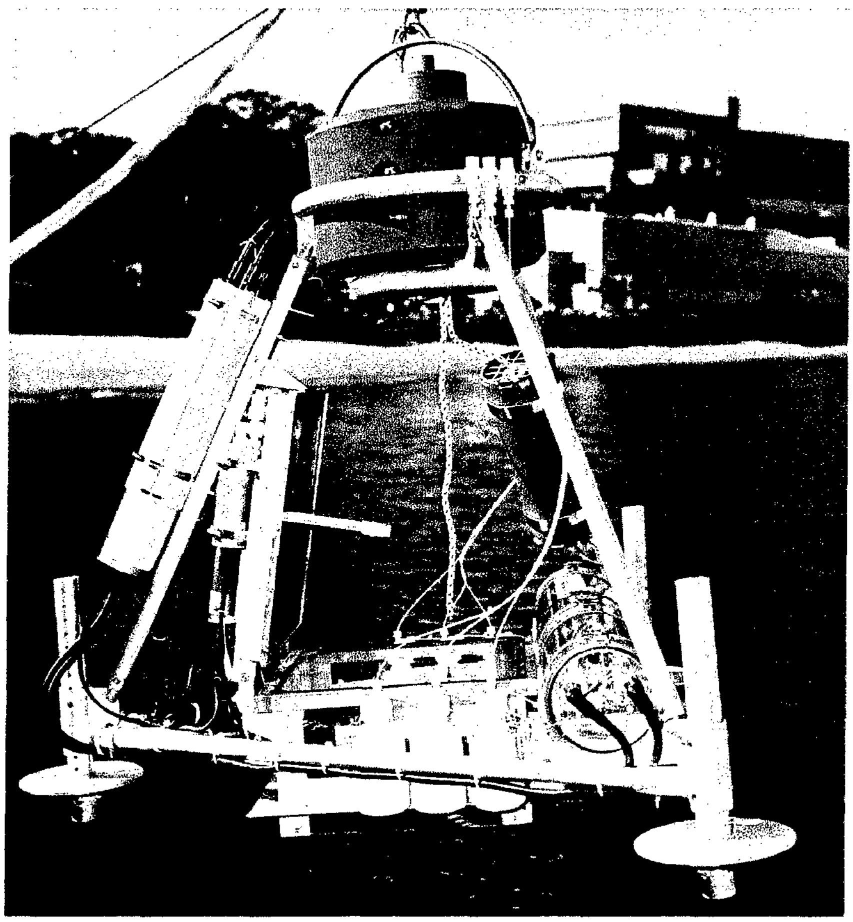

Figure 35. Benthic Flux Sampling Device (BFSD).

Results. Figure 36 shows a typical time-series result from station NSB-5. With the exception of zinc, fluxes of trace metals were low and not strongly correlated with bulk sediment concentrations. This is consistent with the strong binding of metals generally observed in reducing sediments typical of the NAVSTA region. The trace metal flux relationships are illustrated with bar charts showing the trends along a series of transects across the study area in figures 37 and 38. The figures show the trace metal fluxes for the 1995 deployments along with data from earlier 1993 deployments. The zinc fluxes in figure 37 are relatively large so that the other trace metal fluxes are barely visible. The other metal fluxes are replotted in figure 38 without zinc. This demonstrates that zinc is, by far, the trace metal with the largest flux out of the sediments. The first station displayed in both figures is the blank run, followed by the east-west transects near Pier 4 (Stations NSB-2, NSB-3) and Paleta Creek (Stations NSB-4, NSB-5, and NSB-6), and finally the 1993 data. Zinc, nickel, and cadmium fluxes in the 1995 data are high in the east (Stations NSB-3 and NSB-5) and decrease toward the west, and in the 1993 data, higher in the central bay sites compared to north bay sites. The trends for copper and lead fluxes are less clear, with some sites showing fluxes into the sediments. Copper does, however, show the highest fluxes out of the sediments at Stations NSB-3 and NSB-5 where the sediment concentrations of most metals are high.

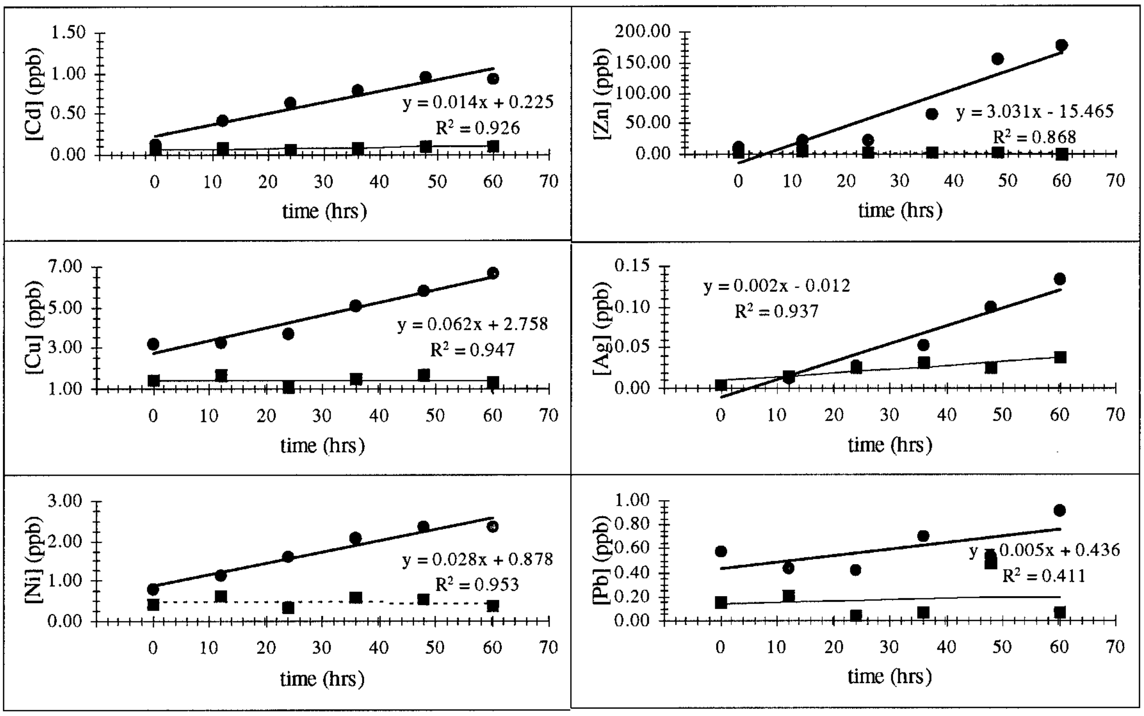

Figure 36. Time series of concentrations in the BFSD for Station NSB-5 (Paleta Creek). Red circles are site measurements and blue squares are blank measurements for comparison.

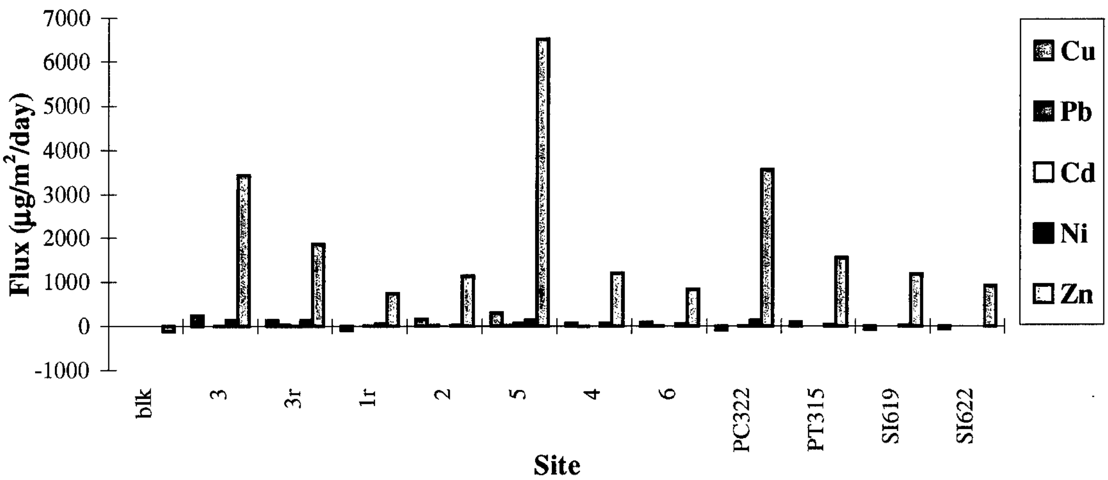

Figure 37. Plot of metal fluxes along east-west transects. Blk indicates blank chamber results.

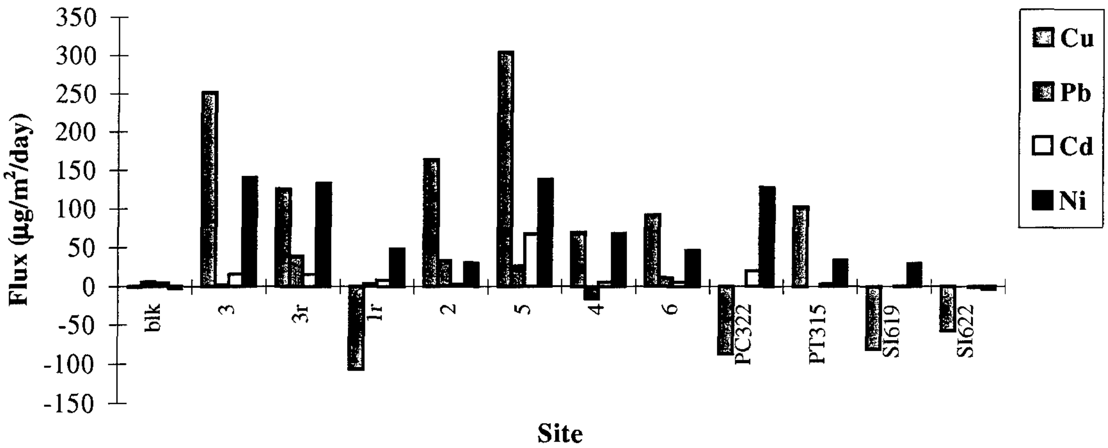

Figure 38. Plot of metal fluxes along east-west transects, excluding zinc. Blk indicates blank chamber results.

As the metal showing the consistently highest fluxes from the sediment, zinc serves as the best example to demonstrate the relative importance of remobilization of metals from the sediment as a source back to the water column. To make these estimates of sediment flux from the NAVSTA area, several assumptions must be made. First, the zinc flux is assumed to be related to the bulk zinc levels in the sediment. This assumption ignores the role played by AVS binding or other factors controlling metal fluxes from the sediment. For zinc, this may not be a major concern since it is the most soluble metal sulfide and zinc fluxes show the best correlation of any of the metals to bulk metal levels in the sediments. The second assumption is that the six stations where fluxes were measured represent the overall range of fluxes in the NAVSTA area, and bulk metal levels at these stations can be used to extrapolate the fluxes throughout the area depending on bulk metal levels.

Looking at the NAVSTA area sediments out to the west side of the navigation channel, a surface area of approximately 3 million square meters (m^2) is present. From the contour map of zinc concentrations in the sediment chemistry section, only approximately 500,000 m^2 are above the ERM value of 410 ppm. The four zinc flux measurements from sediments with these high zinc levels (Stations NSB-2, NSB-3, and NSB-5) average 3100 $\pm$2500 $\mu g \cdot m^{-2} \cdot day^{-1}$. Sediments in the NAVSTA area with zinc levels below ERM values cover approximately 2.5 million m^2 and three flux measurements from sediments with lower zinc levels average 1100 $\pm$200 $\mu g \cdot m^{-2} \cdot day^{-1}$. The overall flux of zinc directly from the sediments in the NAVSTA area is, therefore, 1500 $\pm$600 kg $zinc \cdot yr^{-1}$.

The fluxes of individual PAHs and PCBs were measured at only three stations in this study along an east-west transect including Stations NSB-4, NSB-5, and NSB-6. PCBs were not found above detection level in flux chamber water samples, so no fluxes were calculated. For the PAHs, fluxes for heavier weight PAHs that are commonly found in the sediments were generally from the water column back into the sediment, except at Station NSB-4. Data for fluoranthene, one of the more common PAHs found in the sediments, and total PAHs are given in table 32. As discussed in the sediment chemistry section, Station NSB-4 had a total

PAH value above 90 ppm and probably represents a special case that is not representative of the general NAVSTA area sediments. Just prior to the flux measurements at this location, the creosote pilings were replaced with plastic pilings under a program to remove creosote PAH sources from the bay. Some creosote material appears to have been locally released to the sediments at the end of Pier 8 because normal high total PAH values around the NAVSTA area are closer to the 20 ppm seen at Station NSB-5 in Paleta Creek. This fresh source of creosote at Station NSB-4 led to very elevated fluxes for PAHs. Under the more normal PAH sediment levels seen in the NAVSTA area, it is therefore expected that PAH fluxes from the sediments are minimal. The low fluxes of PCBs and PAHs are expected because of the partitioning of the hydrophobic organic chemicals onto the sediments.

Conclusions. With the exception of zinc, fluxes of trace metals were generally low and not strongly correlated with bulk sediment concentrations. Zinc shows the most consistent and greatest flux out of the sediments, which constitutes a significant input term relative to other known sources. Copper, nickel, lead, and possibly cadmium show more limited flux out of the sediments at some stations. Limited data indicate no PCB fluxes and only limited release of PAHs from stations with elevated PAH bulk levels.

Table 31. San Diego Bay Sediment Flux Data for PAHs.

Station	Fluoranthene ($ng{\cdot}m^{-2}{\cdot}day^{-1}$)	Total PAHs ($ng{\cdot}m^{-2}{\cdot}day^{-1}$)
Blank Run	640 ±260	12600 ±600
Station NSB-4	39000 ±6000	113000 ±35000
Station NSB-5	- 4500 ±2300	- 9300 ±6400
Station NSB-6	- 260 ±180	- 1900 ±4000

6.3.2 Sediment Resuspension by Ships

Resuspended sediments can be a potential source of contaminants in the water column. Therefore, an estimate was made of mass loading of suspended sediments originating from bottom sediment that are resuspended by shear stresses generated during ship movements. The sediment loading was assumed to be introduced only during tug assisted movements (launching/docking) of larger ships (i.e., drafts greater than about 22 ft). The movements considered were for launching movement away from the piers into the main channel, for the initial acceleration in the main channel until underway, and for docking the reverse of this process. Estimates of total resuspended sediment mass loading were made for single ship movement events. The frequency of these movements was determined from Fleet Support Office records. An average daily loading was estimated from these two data sets. Additionally, these estimates were introduced into a sediment transport model in order characterize the transport and fate of the suspended material.

The average daily total mass loading due to vessel movements was assumed to be a product of the average loading because of a single ship movement event times the average daily frequency of vessel movement events. Data for the average loading per event were obtained

from field surveys of suspended sediment taken before and after the ship movements. The before and after data were interpolated onto similar grids and their difference calculated and analyzed. Ship movement events have the added variability that one to three tugs were used depending on ship size. To account for this variance, the movements were weighted according to how many tugs used.

Methods. Four field surveys were conducted for this study: Wak7, Wak8, Wak9, and Wak10. Figure 39 shows the locations for the post-ship-movement survey tracks for these four surveys. Wak7 surveyed the launching of the USS *Shilo* from the south side of Pier 2 with two tugs assisting (3/7/96 15:30, Tide: 0.4 ft low at 16:18). Wak8 surveyed the docking of the USS *Tarawa*, south side Pier 7, with three tugs assisting (3/18/96, 15:00, Tide: -0.9 ft low at 15:42). Wak9 surveyed the launching of USS *Rushmore*, south side Pier 6, with two tugs assisting (4/16/96 9:30, Tide: 5.4 ft high at 9:16). Wak10a surveyed the launching of the USS *Harpers Ferry*, south side Pier 12, with three tugs assisting, and Wak10b, its docking at the south side Pier 6 (4/23/96 8:30, Tide: 0.5 ft low at 8:18).

The field data were separately interpolated onto grids and subtracted from background values. Table 33 shows the average TSS concentrations and total mass values for background, resuspension, and difference for each of the surveys. From these surveys, the total mass loading per ship movement event ranges from 3,800 to 20,400 kg with an average of 11,200 and a standard deviation of 6,500 kg.

Results. Average daily ship movements were calculated from 2-month records (January/February, 1996) of daily work schedules obtained from the Naval Station Fleet Support Office. An estimate of the average daily total mass loading was calculated using the daily ship movements together with the weighting scheme applied to the TSS survey data. Using this scheme, the average daily movements in terms of vessel units (from the Fleet Support Office records) is 17.55 vessel units$\cdot$day^{-1} (table 34). Average daily total mass loading was estimated by calculating the mass loading per vessel unit movement from the surveys found in table 33, and multiplying this by 17.55 vessel units$\cdot$day^{-1}. These estimates range from 15.3 to $71.4\cdot10^{-3}$ kg$\cdot$day^{-1} with an average of $41.7\cdot10^{-3}$ kg$\cdot$day^{-1}, (table 35).

Average TSS concentrations and total mass loading estimates for the surveys differ by a factor of 5. It is difficult to separate what degree of this variability was real and what portion can be attributed to experimental error in the estimates. There were likely areas for experimental error. However, it is likely that a significant fraction of the fivefold difference in TSS concentration and mass loading values were real because of several mechanisms which could cause the actual values to vary. Pier site or bottom bathymetry, ship type or draft, propeller speeds, variability in technique of operators of tugs and of ship captain (the degree to which the ship uses its own propellers can vary widely) may all play a role. It appears that the difference between the ships draft and the bottom bathymetry have a strong influence on the amount of material that gets resuspended. In addition, there may be differences because of ship launching or docking.

Conclusions. In conclusion, an estimate was made of the daily resuspension of sediments due to ship movements in the NAVSTA area. This estimate ranges from $16.7\cdot10^{3}$ to $71.4\cdot10^{3}$ kg$\cdot$day^{-1} with an average value of $41.7\cdot10^{3}$ kg$\cdot$day^{-1}. Although significant experimental error may exist, the majority of this variability can be attributed to the variable conditions during ship movements. This daily input value represents 29 percent of the background mass of suspended sediment for NAVSTA and adjacent shipping channel. In comparison to TSS

loading from Chollas and Paleta Creeks, which drain into NAVSTA, the yearly estimated total sediment resuspension from tug-assisted ship movements was roughly 300 percent of the storm estimated total mass coming from the creeks. From these data together with visual observation of the plumes around the ships and tugs during these movements, it was clear that this loading was a significant source of sediment loading in San Diego Bay and must be considered in mass balance analysis of sediment.

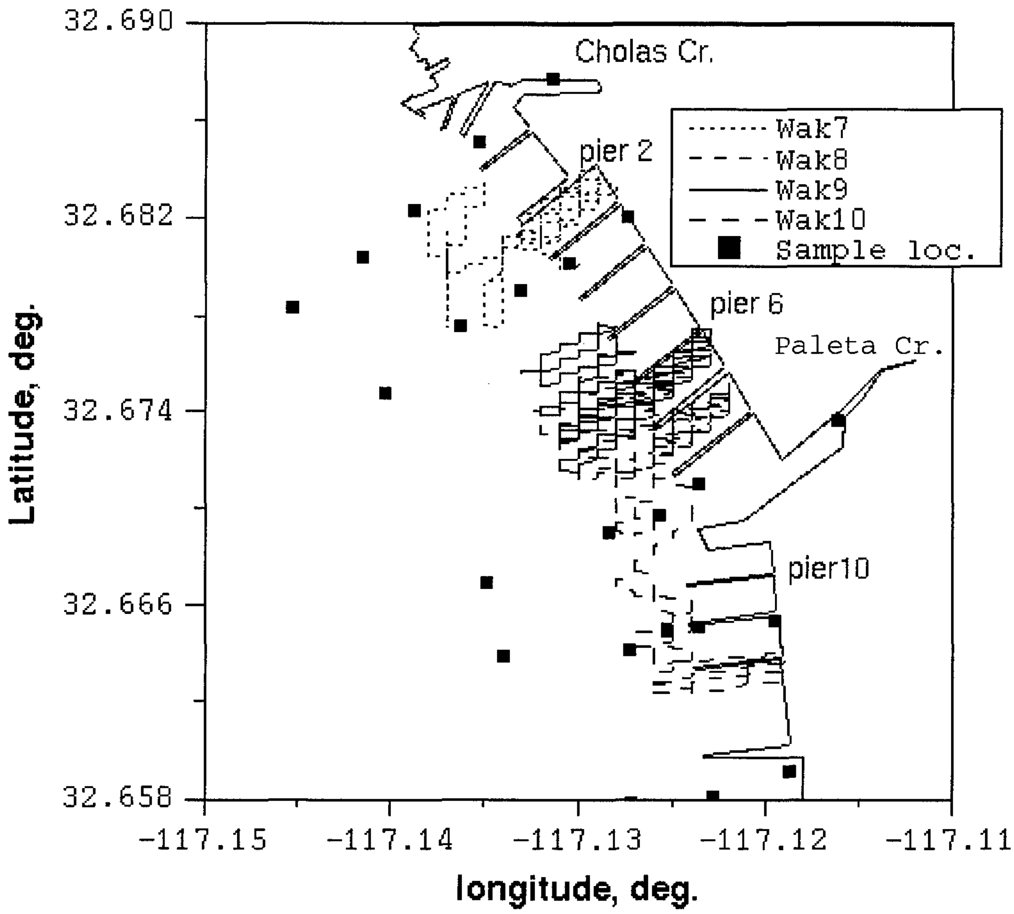

Figure 39. A locator map outlining the NAVSTA and showing the post-ship movement survey vessel shiptracks and the sample locations where bottom sediment grain size analysis was done.

Table 32. Total TSS and concentration values from gridded interpolations of the survey mappings.

Wak7 (2 tugs)	Background	Resuspension	Difference
Ave conc., $mg \cdot L^{-1}$ Total Mass kg Area m^2	2.02 $4.52 \cdot 10^3$ $0.245 \cdot 10^6$	6.94 $15.54 \cdot 10^3$ $0.245 \cdot 10^6$	4.9, 244% $11.0 \cdot 10^3$
Wak8 (3 tugs)			
Ave conc., $mg \cdot L^{-1}$ Total Mass kg Area m^2	1.68 $6.19 \cdot 10^3$ $0.402 \cdot 10^6$	7.23 $26.62 \cdot 10^3$ $0.402 \cdot 10^6$	5.5, 324% $20.4 \cdot 10^3$
Wak9 (2 tugs)			
Ave conc., $mg \cdot L^{-1}$ Total Mass kg Area m^2	2.26 $9.11 \cdot 10^3$ $0.442 \cdot 10^6$	3.20 $12.9 \cdot 10^3$ $0.442 \cdot 10^6$	0.9, 41% $3.8 \cdot 10^3$
Wak10a (3 tugs)			
Ave conc., $mg \cdot L^{-1}$ Total Mass kg Area m^2	6.61 $19.59 \cdot 10^3$ $0.324 \cdot 10^6$	12.07 $35.78 \cdot 10^3$ $0.324 \cdot 10^6$	5.5, 83% $16.2 \cdot 10^3$
Wak10b(3 tugs)			
Ave conc., $mg \cdot L^{-1}$ Total Mass kg Area m^2	5.46 $17.66 \cdot 10^3$ $0.353 \cdot 10^6$	6.81 $22.01 \cdot 10^3$ $0.353 \cdot 10^6$	1.35, 25% $4.4 \cdot 10^3$
Average +/- S.Dev.			
Ave. conc., $mg \cdot L^{-1}$ Total Mass kg	**3.61 +/-2.02** **11.4 +/-6.1 $\cdot 10^3$**	**7.25 +/-2.83** **22.6 +/-8.2 $\cdot 10^3$**	**3.3 +/-1.6** **11.2 +/-6.5 $\cdot 10^3$**

Table 33. Average number of daily ship movements for NAVSTA.

Month	Ships moved	Tugs Used	Tugs/Ship	Ships/Day	Vessel Units/Day
Oct '95	150	265	1.77	4.84	18.25
Nov '95	134	229	1.71	4.47	16.58
Jan '96	132	236	1.79	4.26	16.14
Feb '96	127	219	1.72	4.38	16.29
Mar '96	165	267	1.62	5.50	19.91
Apr '96	165	270	1.64	5.50	20.02
May '96	136	215	1.58	4.39	15.71
Average	**144**	**244**	**1.69 +/-0.07**	**4.76 +/-0.5**	**17.55 +/-1.7**

Table 34. Average daily total mass of resuspended sediment for NAVSTA.

	Resuspension (kg/ vessel unit)	Avg. Daily Resuspension (kg/day)
Wak7	$2.76 \cdot 10^3$	$48.44 \cdot 10^3$
Wak8	$4.07 \cdot 10^3$	$71.42 \cdot 10^3$
Wak9	$0.95 \cdot 10^3$	$16.67 \cdot 10^3$
Wak10a	$3.24 \cdot 10^3$	$56.86 \cdot 10^3$
Wak10b	$0.87 \cdot 10^3$	$15.27 \cdot 10^3$
Average +/- S.Dev	**2.4 +/-$1.3 \cdot 10^3$**	**41.7 +/- $22.3 \cdot 10^3$**

6.3.3 Desorption of Chemicals from Resuspended Sediments

A study was conducted to determine the amount of trace metals released back into the water column from the resuspension of sediments in the NAVSTA area described in Section 6.3.2 above. While resuspension events may serve to redistribute metals associated with sediment particles, the release of metals back to the water will only take place if desorption occurs during this resuspension process. To evaluate this, sediments from NAVSTA were collected and tested to determine the rate at which metals could be re-released under simulated resuspension conditions.

Methods. Sediments from Station NSB-3 were selected for this experiment because they represent the sediments with the highest metals levels in the NAVSTA area and can be used to estimate the upper limit of metals released back into the water. One gram of sediment from Station NSB-3 was placed in 1 liter of clean, aerobic seawater to determine the rates that metals were released from continually resuspended sediments.

Results. Table 36 provides the data for a series of metals released from resuspended sediments over an 8-hour period. The data show that all metals measured had some degree of release, and consistent with benthic flux results, zinc showed the largest release. From these results, we can predict both the expected increase in water column concentration of dissolved metals during a resuspension event, and the annual loading contribution to the water column from all resuspension events. To estimate the increase in water column concentration, we take the increase in dissolved metal concentration between hour 0 and hour 0.5 (table 36), and scale it by the ratio of the experimental TSS concentration ($1\ g \cdot L^{-1}$) and the average measured TSS concentration increase in the resuspension plumes ($3.3\ mg \cdot L^{-1}$; table 33). From this we find that the expected increase in water column concentration above typical background levels ranges from a low of 0.1 percent for copper to a high of 1.2 percent for cadmium (table 37). This increase is unlikely to be detectable by direct measurement and is unlikely to lead to significant changes in ecological effects above the existing background.

Using zinc as an example, calculations can be made of the annual water column load due to resuspension events. Assuming each gram of resuspended sediment is equilibrating with seawater, it appears to take at least 0.5 hours before concentrations reach equilibrium and stabilize. Assuming the release rate obtained during the first 0.5 hours of the experiment represents the release rates during resuspension, zinc is released at the rate of $18.6\ mg \cdot g^{-1} \cdot 0.5\ hour^{-1}$. If material remains resuspended in the water column for an average of 2.5 hours, and

a value of 41700 ±22300 kg·day^{-1} is used for the amount of resuspension in the NAVSTA area, estimates of 1400 ±760 kg zinc·yr^{-1} are released from resuspended sediments.

Conclusions. The estimated zinc released from resuspended sediments is comparable to the 1500 ±600 kg zinc·yr^{-1} fluxing directly from the sediment. And both these zinc releases from the sediment are smaller than the source of zinc from Chollas and Paleta Creeks into the NAVSTA area, which were estimated to be 2300 to 3400 kg zinc·yr^{-1} from 10 to 15 rain events per year. Results from a similar analysis of the all metals listed in table 36 are shown in table 37. Although the estimates of release from resuspension events are lower than other sources, the amount of material remobilized is significant and represents an aspect of contaminant fate in the vicinity of NAVSTA that warrants examination by transport and fate modeling, described in the next section.

Table 35. Trace metals released during aerobic resuspension of Station NSB-3 sediments.

	Concentrations (µg·L^{-1})				
Time (hr)	**Cd**	**Cu**	**Ni**	**Pb**	**Zn**
0	0.069	0.29	0.41	0.04	1.4
0.1	0.197	0.78	0.90	0.19	19
0.5	0.376	1.18	0.89	0.20	20
2.0	0.246	1.05	1.05	0.23	16
8.0	0.358	1.64	0.98	0.19	16

Table 36. Estimated metal loading and increase in water column concentrations from sediments resuspended by ships in the NAVSTA region.

	Cd	**Cu**	**Ni**	**Pb**	**Zn**
Experimental Data					
Delta C (ug·L^{-1})	0.307	0.89	0.48	0.16	18.6
Delta t (hours)	0.5	0.5	0.5	0.5	0.5
Water Volume (L)	1	1	1	1	1
Sediment Volume (g)	1	1	1	1	1
flux ug(metal)·g^{-1}(sed.)·hr^{-1}	0.614	1.78	0.96	0.32	37.2
Water Column Concentrations					
Avg. Plume TSS Increase (mg·L^{-1})	3.5	3.5	3.5	3.5	3.5
Plume Diss. Metal Increase (ug·L^{-1})	0.0011	0.0031	0.0017	0.0006	0.0651
Background Water Conc. (ug·L^{-1})	0.09	3.0	0.66	0.33	11.3
% Increase over Background	**1.2**	**0.10**	**0.25**	**0.17**	**0.58**
Remobilization Loading					
Resuspended Sediment (kg·day^{-1})	41700	41700	41700	41700	41700
Time in Suspension (hours)	2.5	2.5	2.5	2.5	2.5
Total Resuspension Flux (kg·year^{-1})	**23**	**68**	**37**	**12**	**1400**

6.4 TRANSPORT AND FATE MODELING

6.4.1 Circulation and Transport Modeling and Validation

To provide predictions of how sediments would be transported in the NAVSTA region, it was recognized that an efficient and accurate hydrodynamic model of the bay was required. Although some numerical modeling of the San Diego Bay has been performed in the past [19], the models used in these efforts were not considered to reproduce the circulation of the bay in a manner that would accurately predict the transport of sediment-bound chemicals. In addition, none of the previous models had undergone significant validation to establish the level of accuracy to which they reproduced water flow within the bay. Thus, a significant aspect of this study included the setup, calibration, and validation of a high-resolution, numerical hydrodynamic model of San Diego Bay. Another objective of this study was to provide a quantitative characterization of the hydrodynamics and properties of tides and tidal current of San Diego Bay and in particular for the region of the bay near NAVSTA. Typically, when hydrodynamic field data are available both the spatial and temporal coverage is sparse. Once a numerical hydrodynamic model has been calibrated and verified, it can provide far greater resolution than ever obtainable from field measurements.

Methods. The numerical hydrodynamic model implemented for San Diego Bay is the depth-averaged tidal and residual circulation model known as TRIM-2D (Cheng et al., 1993), with some improvements. It has a grid that covers an area of 20.0 km by 15.4 km; the western boundary is located about 5 kilometers west of Point Loma. Since no suitable boundary condition data are available at the entrance to the bay, the numerical model domain is extended into the adjacent coastal ocean. Since it was found initially that no significant differences between results for fine and coarse grids exist in terms of tides or tidal currents, a coarse grid (100 m) was used for most of the study. The model was calibrated using historical data and verified against two independent field data sets representative of summer and winter conditions for San Diego Bay. For a more detailed description of the model, see Cheng et al. (1993).

A comprehensive data collection program was conducted jointly by the U.S. Geological Survey (USGS), SSC San Diego, and the U.S. Army Corps of Engineers (USACoE) in 1993 and 1994. Both mechanical current meters and acoustic Doppler current profilers (ADCPs) were used in this field data program. Time-series data of tides and tidal currents were collected in two systematic efforts in San Diego Bay in 1983 and in 1993 and 1994. The 1983 data set was used for calibration and the 1993 and 1994 data sets were used for verification. Prior to 1993, the mechanical current meters collected all tidal current data. Of the total 14 current meter moorings deployed in 1983, only data from eight current meter records were of sufficient length and quality. In some cases, the lengths of the time-series had to be shortened from the deployment period for analysis because part of the data were corrupted due to instrument failure and marine fouling. In model verifications, the model results were compared against data sets representing the summer condition in 1993 and winter condition in 1994. For the summer conditions (Case 1), data were collected by both the conventional current meters and ADCPs. For the winter simulation (Case 2), only conventional current meter data were collected and no ADCP data were available.

Results. In the model calibration, the numerical model reproduced the tidal elevation to within about 1 cm, and the tidal phase to within about 1.5°. Calibration results also showed that, on average, the model-simulated tidal velocities (M_2 and K_1) differ with field data by about 1 $cm \cdot s^{-1}$, but the differences in tidal current direction and phase are on the order of 10°. The uncertainty in model grid (bathymetry) and problems inherent to mechanical current meters are the probable causes of these discrepancies. Furthermore, it is not certain how well the fixed depth measurement of tidal currents can be used to represent the depth averaged tidal currents. This situation is particularly acute in shallow regions where some of the current meter data were collected. In view of these possible shortcomings in the field data, no further attempts were made to improve the agreements between simulations and measurements. The numerical model calibration was considered satisfactory and successful.

In model verifications, the model results were compared against two independent field data sets representing the summer condition in 1993 and winter condition in 1994. In both cases, the harmonic constants of the tidal elevations were in excellent agreement with field data at Balllast Point, San Diego, and South San Diego. For all four major tidal constituents, M_2, K_1, O_1, and S_2, the mean amplitude difference between the model results and field observations was about 1 cm or less. There was about 1° or less in phase difference for all tidal constituents except for S_2, which had a difference of between 2° and 4° (4 to 8 minutes).

The results of model verification against tidal currents showed that, for Case 1, when the ADCP data were available at all three ADCP sites, the numerical model reproduced the magnitude of the major and the minor axes of tidal ellipses for M_2 and K_1 to about 1 $cm \cdot s^{-1}$. At SDBB1 near the entrance to the Bay, the major axis difference for M_2 was 2.46 $cm \cdot s^{-1}$. The maximum differences in phase and current direction were less than 8^{0}; this could be caused by the uncertainties in the model bathymetry and/or the three-dimensional effects of the flow. The comparisons between the numerical model and the ADCP data are considered satisfactory and successful (table 38). However, in both Cases 1 and 2, the comparisons at other sites, where the field data were collected by mechanical current meters, are deemed marginally satisfactory. Several reasons suggest that these discrepancies were caused by errors in the field data such as marine growth, although, as pointed out before, the fixed depth measurement of tidal currents might not be representative of the depth averaged tidal currents.

The verified numerical model provides a quantitative characterization of the hydrodynamics and properties of tides and tidal current of San Diego Bay and, in particular, for the region of the bay near NAVSTA. The tidal circulation for a typical spring tidal condition was examined for the NAVSTA region. Figure 40 shows the maximum ebb currents generated during this tide. The faster moving water is localized to the deeper main shipping channel. Currents speeds in the channel range from 30 to 40 $cm \cdot s^{-1}$ and are generally aligned with the channel axis. In the NAVSTA area, currents are about 5 $cm \cdot s^{-1}$ near the Quay Wall and 10 to 15 $cm \cdot s^{-1}$ at the ends of the piers. Figure 41 shows the maximum flood currents for a typical spring tide. The flood stage currents are typically higher than those during the ebb. In the main shipping channel, current speeds range between 50 to 60 $cm \cdot s^{-1}$. In the NAVSTA area, currents are about 5 $cm \cdot s^{-1}$ at the quay wall and reach 15 to 20 $cm \cdot s^{-1}$ at the ends of the piers. During peak flood, a large-scale eddy can be seen in the shallow region across the shipping channel from the north end of the NAVSTA.

San Diego Bay typically has very mild bottom shear stresses and, hence, mild bottom erosion. Under typical conditions, the minimum bottom shear needed for the movement of fine bottom sediments is about 1.0 dynes·cm^{-2}. The model was used to estimate the time averaged and maximum bottom shear stress for the NAVSTA area. In the pier areas and shipping channel, the average bottom shear stress does not exceed 0.25 dynes·cm^{-2}. Higher values near 0.5 dynes·cm^{-2} can be found across the shipping channel at the north and south ends of these shallow regions. Figure 42 shows the maximum bottom shear stress. In the NAVSTA area and adjacent shipping channel, the bottom shear does not exceed 0.75 dynes·cm^{-2} and is below levels needed to cause erosion. Areas just north and south of NAVSTA show values near 1.0 dynes·cm^{-2} and may have mild erosion occurring during the onset of a strong flood tide or near the end of a strong ebb.

Table 37. Model Verification at ADCP sites, Summer, 1993.

	M2				K1			
	Major	**Minor**	**Direction**	**k'**	**Major**	**Minor**	**Direction**	**k'**
Model-SDBB1	30.25	1.95	354.9	178.9	10.63	2.07	351.7	353.4
Data-SDBB1	27.64	-0.25	353.5	180.4	8.94	0.83	347.7	8.6
Difference*	2.61	2.2	1.4	-1.5	1.69	1.24	4.0	-15.2
Model-SDNB1	31.31	0.43	58.7	177.1	10.08	0.79	56.5	1.1
Data-SDNB1	31.72	-0.20	58.5	176.3	9.59	0.81	57.5	359.3
Difference*	-0.41	0.63	0.2	0.8	0.49	-0.02	-1.0	1.8
Model-SDNB2	27.24	1.04	133.9	178.4	9.09	0.75	130.1	2.6
Data-SDNB2	26.38	0.06	135.9	182.7	8.75	0.76	136.4	1.4
Difference*	0.86	0.98	-2.0	-4.3	0.34	-0.01	-6.3	1.2

**Difference = Model Results — Measured Time-series*

Conclusions. This section reports the calibration, verification, and application of the TRIM model to simulations of circulation and transport in San Diego Bay and in the NAVSTA region in particular. In the model calibration, the numerical model reproduced the amplitudes of tides to within 1 cm and the maximum phase difference to less than 1.5°. The agreements achieved in model calibration for water levels are considered to be fully satisfactory. The model-simulated tidal velocities (M_2 and K_1) differ with field data by about 1 cm·s^{-1}, but the differences in tidal current direction and phase are on the order of 10°. The uncertainty in model grid, problems with mechanical current meters, and the ability of fixed depth measurement of tidal currents to represent the depth averaged tidal currents are the probable cause of these discrepancies.

. For model verification, the model results were compared against two independent field data sets representing the summer condition in 1993 and winter condition in 1994. For all four major tidal constituents, M_2, K_1, O_1, and S_2, the mean amplitude difference between the model results and field observations is about 1 cm or less. There is about 1° or less in phase difference for all tidal constituents except for S_2, which has a difference of between 2° and 4° (4 to 8 minutes). At all three ADCP sites, the numerical model reproduced the magnitude of the major and the minor axes of tidal ellipses for M_2 and K_1 to about 1 cm·s^{-1}. At SDBB1

near the entrance to the Bay, the major axis difference for M_2 was 2.5 $cm \cdot s^{-1}$. The maximum differences in phase and current direction were less than 8^0. Differences are attributed to uncertainties in the model bathymetry and/or the three-dimensional effects of the flow. The comparisons between the numerical model and the ADCP data are considered satisfactory and successful. However, the comparisons at other sites, where the field data were collected by mechanical current meters, are deemed marginally satisfactory.

The verified numerical model has been used to simulate circulation and transport in the NAVSTA region. Results indicate that currents and bottom stresses within the piers are generally too weak to drive significant sediment resuspension.

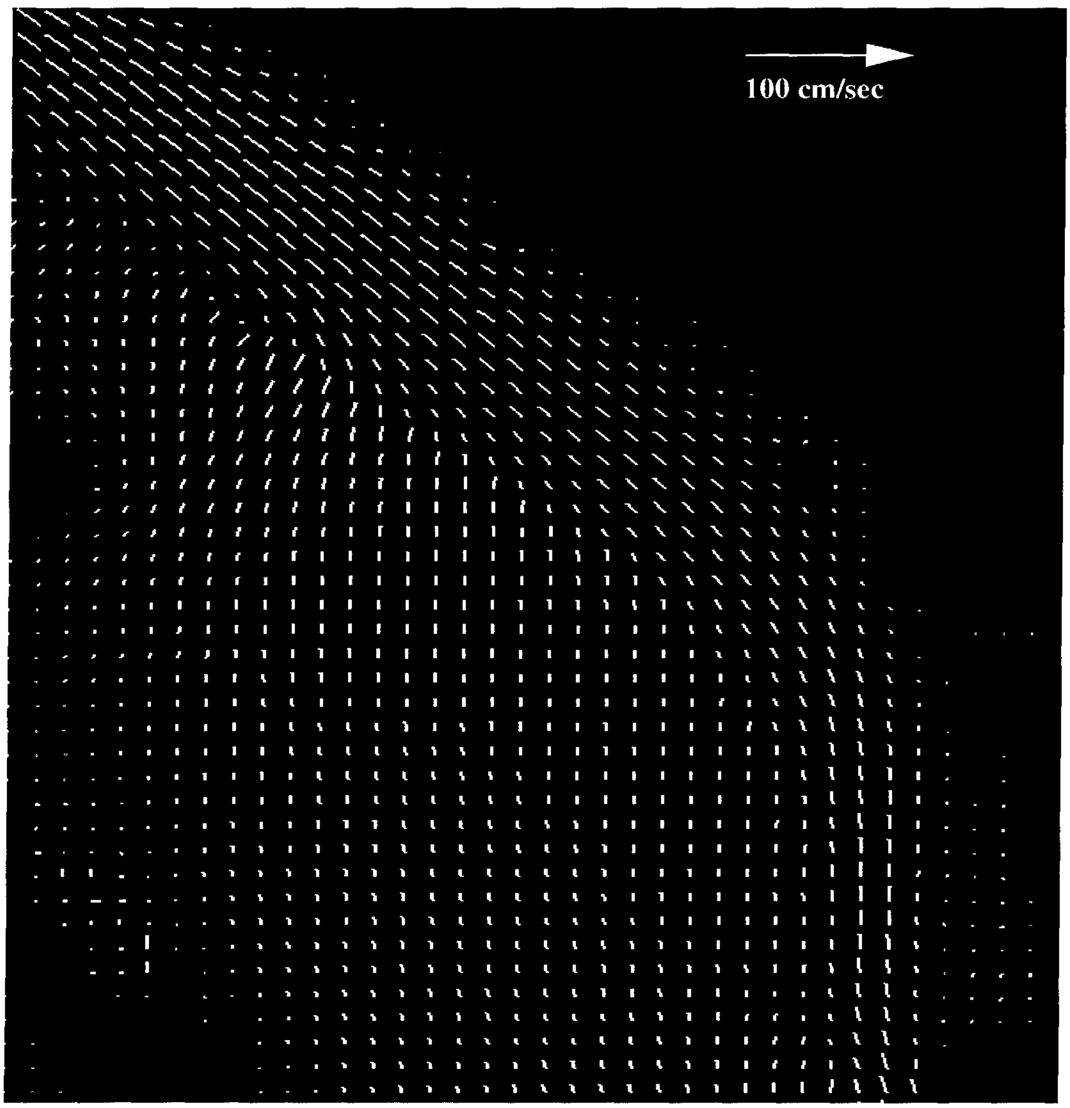

Figure 40. Depth-averaged water currents during a typical ebb tide. High values are about 40 $cm \cdot s^{-1}$ in the main shipping channel under the Coronado Bridge. Depth is color-mapped with deeper water shown as dark blue.

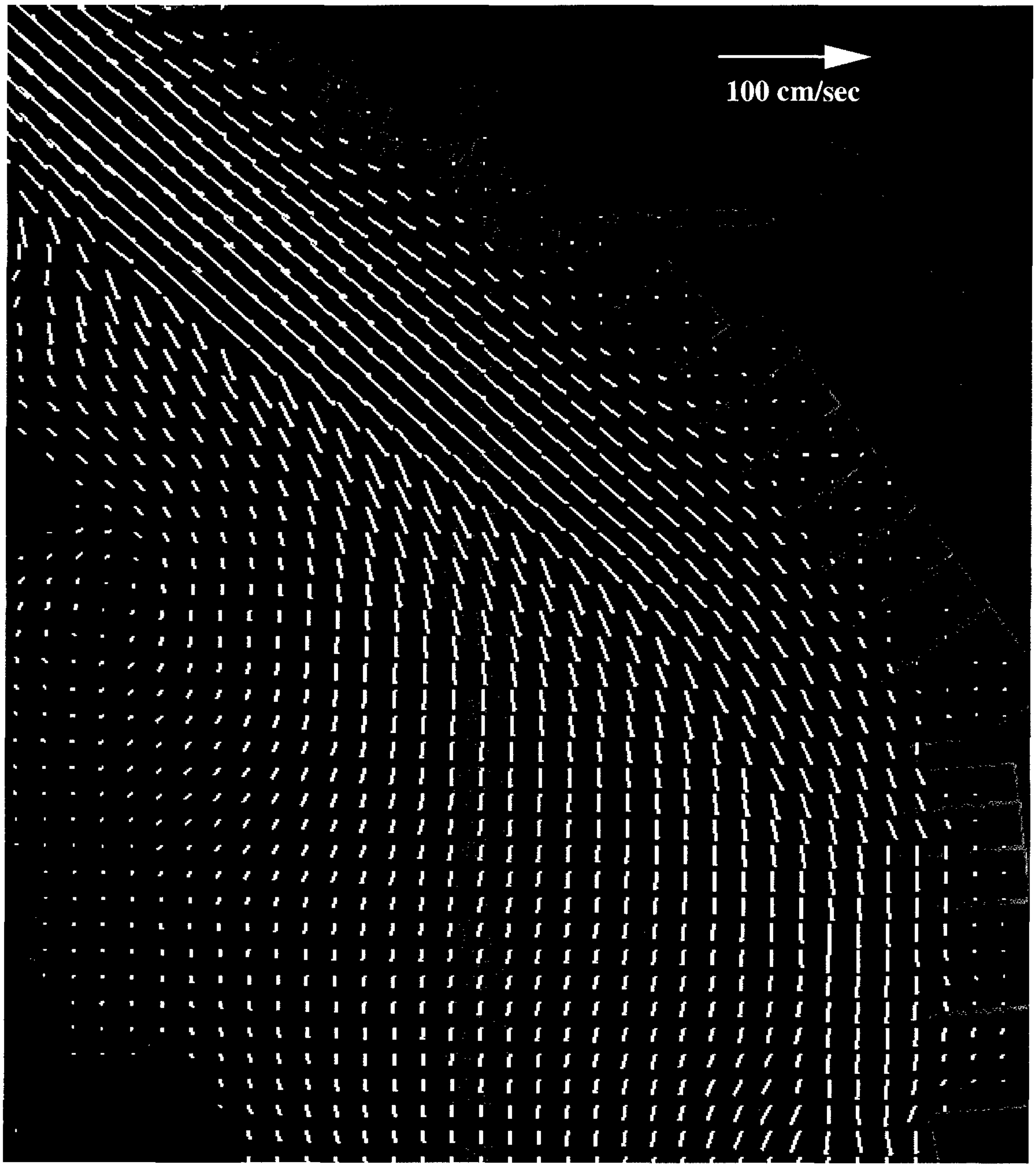

Figure 41. Depth-averaged water currents during a typical flood tide. High values are about 60 $cm \cdot s^{-1}$ in the main shipping channel under the Coronado Bridge. Depth is color-mapped with deeper water shown as dark blue.

Figure 42. Maximum bottom shear stress for the NAVSTA area. The bottom sediments in the NAVSTA area and adjacent main shipping channel have a maximum bottom shear of less than 0.6 dynes·cm^{-2}.

6.4.2 Sediment Transport Modeling

The sediment transport model (TRIM-SED) was developed based on the validated hydrodynamic model described in Section 6.4.1 above. The model was used to evaluate the transport of sediments and associated chemicals (e.g., copper and PAHs) in San Diego Bay. The hydrodynamic calculations provide flow fields that drive the transport of solids and chemicals in the water column. Exchanges of solids between sediment bed and water column are simulated using the most up-dated knowledge about these processes, including erosion and deposition (Ariathruai et al., 1977; Lick, 1986). In the NAVSTA region, some resuspension of bottom sediments may be caused by the shear induced by currents and wind waves; however, the majority of resuspension probably driven by ship movements (see Section 6.3.2 above). In addition, the input of new particulate matter to the region occurs primarily from creeks and rivers that flow episodically during the winter. The sediment input, resuspension, transport, and deposition associated with these processes are described below.

Tidal Transport of Sediment Resuspended by Ships. The resuspension of bottom sediments by boat-tugging and docking of large vessels near NAVSTA is a concern for its role in the migration of sediments and associated contaminants. Previous field measurements have shown that a strong correlation exists between levels of contaminants and the amount of fine particles in sediments (Chadwick, 1995). Tugging and docking activities in the vicinity of naval piers resuspend these sediments and sorbed contaminants from the bottom into the water column. These sediments and chemicals are then transported by tidal currents and deposit in other regions of the bay. Because of the large number of ship movements, and the large shear forces generated by the strong thrust of propellers, tugging and docking activities are probably responsible for a major portion of bottom-sediment resuspension in the NAVSTA region. While resuspension of bottom sediments during tugging and docking activities has often been observed in the field, quantitative descriptions of the processes are lacking. This study attempts to predict and quantify, in a statistical manner, the fates of bottom sediments resuspended into the water column during tugging and docking in the area within the NAVSTA piers where a majority of docking activities occur.

Methods. In the spring of 1996, SSC San Diego conducted several measurements of the suspended solids concentrations in the water column during ship-docking events in the areas of the NAVSTA piers (see Section 6.3.2). Results from the field resuspension measurements were combined with ship movement statistics to develop the input for the sediment transport modeling. Only tidal currents were considered for sediment transport. Resuspension of bottom sediments by processes other than tugging or docking were not considered. In addition, since most of the tugging and maneuvering occurs within the piers, resuspension outside the piers by was not investigated. Several terminologies are defined for convenience. An "event" is any docking (resuspension) that might occur or was assumed to occur. "Samples" are a series (11 for each pier area) of designed events, which covered all the possible docking events during a 24-hour period. For each pier area, the samples include 11 docking events, occurring at 12 different tidal stages over a 24-hour period. "Scenarios" are defined as the docking events that have actually occurred or are assumed to occur.

Results. For the modeling simulations, docking activities and associated resuspension events were treated as stochastic processes, of which statistics were estimated from the work schedules and field measurements summarized in the section on sediment resuspension by ships. A uniform distribution of docking events over all tidal stages was assumed. Simulations were carried out for dockings in three pier areas including between Pier 2 and Pier 3, between Pier 6 and Pier 7, and between Pier 12 and 13. For each docking event, it is assumed that each tugboat corresponds to 1 unit and each ship tugged corresponds to 2 units, contributing to the resuspension of bottom sediments. On average, 3.69 units were required for each docking event, 4.76 docking events occurred for each day and, hence, 17.55 units took place each day. The event-averaged sediment mass loading was approximately 5250 kg·docking^{-1} (table 39).

Table 38. Daily docking events and event-averaged resuspended sediments.

	Estimated from 2-Month Record	**Values used in the Stochastic Model**
Resuspension Units* per Docking Event	3.69	3.51
Daily Docking Events	4.76	5
Daily Docking-Induced Resuspension Units	17.55	17.55
Resuspended Sediments per Docking Event	5250 Kg	5250 Kg

** One tug boat corresponds to one resuspension unit and each ship tugged corresponds to resuspension units.*

The input to the stochastic model includes the base response functions that represent the footprints of the deposited sediments of the suspended solids resuspended by docking at different tidal stages. It is clear from the model that most of the resuspended sediments deposit within and in the vicinity of the piers. Particles with higher settling velocities such as fine sand and coarse sand deposit at faster rates. As the settling velocity decreases, removal rate of water-column suspended solids is reduced and more suspended solids are transported by hydrodynamic currents and deposit at other regions. The footprints of sediment deposits strongly depend on the tidal stages when dockings occur. To understand the dependence of distributions of sediment deposits on tidal stages, the base response functions are integrated across the horizontal direction (across the bay). For the locations where bottom sediments are initially resuspended, the deposited sediments at the same locations constitute about 16 percent of the initial sediment mass for clay, 25 percent for silt, 60 percent for fine sand and over 70 percent for coarse sand. Compared to the total initial sediment mass, sediment deposits that migrate to the upper and lower portions of the areas where dockings occur vary with 20 to 70 percent for clay, 10 to 70 percent for silt, 1 to 40 percent for fine sand, and 1 to 20 percent for coarse sand, depending on the tidal stages when dockings occur. Sediments deposit within the areas of less than 200 meters constitute over about 50 percent of the initial mass of clay, about 70 percent of the initial mass of silt, about 85 percent of the initial mass of fine sand and over about 95 percent of the initial mass of coarse sand.

Out of the three pier areas, sediments resuspended in the area of Pier 12 and 13 are most likely to be dispersed and deposited to adjacent regions, due to relatively large tidal currents. Transport of sediments by tidal currents is minimal for sediments resuspended in the area of Piers 6 and 7. These results are consistent with the distributions of hydrodynamic circulation in those areas, both measured and predicted previously (Cheng et al., 1996).

The portions of sediments and associated PAHs that settle back within the piers, and that are transported out of the piers, was calculated. Results are listed in table 40. It is shown that 22.5 percent of the initially resuspended clay particles settle to the bottom within the piers, and 77.5 percent are transported and settle to the bottom outside the piers. For silt, 33.6 percent remain within the piers and 66.4 percent are transported out of the piers. The portions remaining within the piers increase to 68.3 percent and 89.4 percent for fine sand and coarse sand, respectively. For total PAHs, 39.7 percent remain within the piers, and 60.3 percent settle to the bottom outside the piers. For total PAHs associated with each sediment categories, 20.5 percent of the total PAHs remaining within the piers are associated with clay/silt and 14.6 percent and 4.6 percent of the total PAHs remaining within the piers are associates with fine sand and coarse sand, respectively. Of the total PAHs transported outside the piers, 53.1 percent are associates with clay and silt, and 6.7 percent and 0.5 percent of the total PAHs transported outside the piers are associated with fine sand and coarse sand, respectively.

Table 39. Final depositions of suspended solids and total PAHs (percentage of the initial masses).

Sediments/Total PAHs	Portions Within the Piers	Portions Outside the Piers
Clay	22.5%	77.5%
Silt	33.6%	66.4%
Fine Sand	68.3%	31.7%
Coarse Sand	89.4%	10.6%
Total Sediment	45.3%	54.7%
PAHs in Clay/Silt	20.5%	53.1%
PAHs in Fine Sand	14.6%	6.7%
PAHs in Coarse Sand	4.6%	0.5%
PAHs in Total Sediments	39.7%	60.3%

Tidal Transport of Stormwater Inflows. San Diego Bay has three relatively major creeks/ rivers in the vicinity of NAVSTA that sometimes have significant inputs into the bay (see Section 6.2.1). During the majority of the year, the flows in these creeks are insignificant; however, in the winter months during storm events, these creeks provide significant freshwater input, elevated suspended sediment, and chemical loading into the bay. Two of the creeks drain directly within the NAVSTA area, Chollas Creek located at the north end near

Pier 1, and Paleta Creek near the midpoint of NAVSTA between Piers 8 and 9. The third, Sweetwater River, drains into the Bay on the east shoreline about 3/4 mile south of NAVSTA (figure 43). This study was undertaken to understand the role these inputs play in supplying sediment and contaminants to the NAVSTA region.

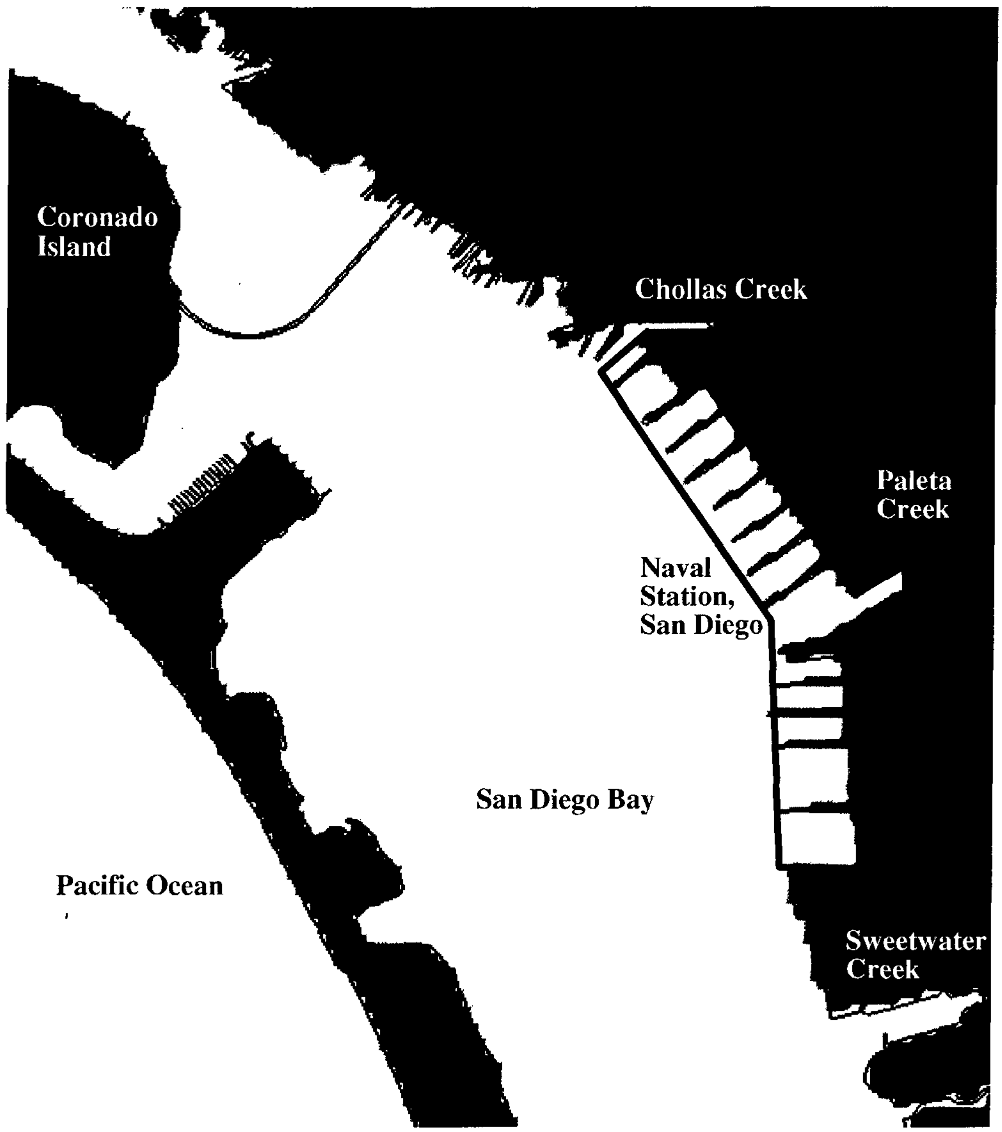

Figure 43. Locator map for Chollas and Paleta Creeks and Sweetwater River and their relation to the wetted area of NAVSTA.

Methods. The transport and fate of creek outfall, suspended solids, and chemicals were examined using field data collected using creek sampling stations together with a detailed baywide computer transport model. For this study, a hydrodynamic/sediment transport model, TRIM-SED, was modified to include multiple internal (creek) flow inputs, each associated with multiple chemical loadings. Creek outfall field data were analyzed and used as input to the model for the creek loadings. The creek outfall flows were modeled as a half-

sine wave matched to storm runoff duration and total flow volume. Three storm events were modeled simulating weak, average, and strong storm events. These simulations provided some estimated limits that characterize the loading and baywide transport of creek storm outfalls.

Model outputs included baywide water column suspended sediment and chemical levels, footprints of suspended sediment and chemical levels that have settled on the bottom sediment. These data can be generated throughout the storm and post-storm periods. TSS and copper concentrations were held constant throughout the events and matched to field data. TSS was modeled using four size fractions centered at 6, 30, 100, and 250 µm. Distributions for these size fractions were taken from Paleta Creek and Sweetwater River data (no data were available from Chollas and Switzer Creeks). Field studies indicate that most copper is bound to particles less than 25 µm. Therefore, copper was modeled as bound to 10 µm particles, which represents the mid-range between 0 and 25 µm. Model parameters for strong, average, and weak events for Chollas and Paleta Creeks, and Sweetwater River, were obtained from an analysis of the stormwater sampling data. A medium spring tidal condition, tidal range of 7 ft was used for all three storm condition simulations.

Results. From the model results it was found that the spatial transport and fate of fine TSS particles (less than 12 µm) and associated chemicals (e.g. copper) extends throughout the bay. The 12 to 55 µm particles, although also transported to the front and back sections of the bay are localized to the eastern shoreline. The medium-size particles are confined to areas within 1 to 2 km of the creek outfalls, and the coarse particles settle out right at the outfalls. Figures 44 through 47 show the predicted spatial distributions of sediment deposition from average storm events.

Since the outfalls of Chollas and Paleta Creeks are within NAVSTA, a large fraction of storm event TSS and copper loading gets deposited on the bottom sediments of NAVSTA. The model was run for a range of conditions using strong, average and weak storm events. For the strong and weak events, about 35 percent of the total loading from Chollas and Paleta Creeks and Sweetwater River settles to the bottom within NAVSTA (table 41). For the average storm event, this drops to 13 percent. This is likely due to peak flow for the average storm event occurring during a higher current flow period. In terms of TSS mass loading, 978, 63.5, and 43.8 $\cdot 10^3$ kg were deposited during the strong, average and weak events. By taking the yearly average rainfall, and dividing it by the rainfall characterizing the strong, average, and weak storm events (1.3, 0.71, and 0.35 in) in order to characterize the varying conditions throughout a year, a range of loading scenarios composed of either all strong, all average, or all weak storms were calculated (table 41). Over a year, depending on the type of storms, estimates of 997 to $8411 \cdot 10^3$ $kg \cdot yr^{-1}$ were derived. The yearly NAVSTA loading comprised of all average or all weak storms was about the same at 10^6 $kg \cdot yr^{-1}$. The loading from a year comprised of all strong storms was about an order of magnitude higher, or $8 \cdot 10^6$ $kg \cdot yr^{-1}$. For copper associated with these particles, about 27 percent of the total loading from the three creeks remains on the bottom sediments within the NAVSTA for all three storm events. This amounts to 66.5, 7.9 and 1.67 kg for the strong, average and weak storms, or a yearly average of 572, 124, or 52 $kg \cdot yr^{-1}$ from years containing either all strong, average, or weak storms (table 41).

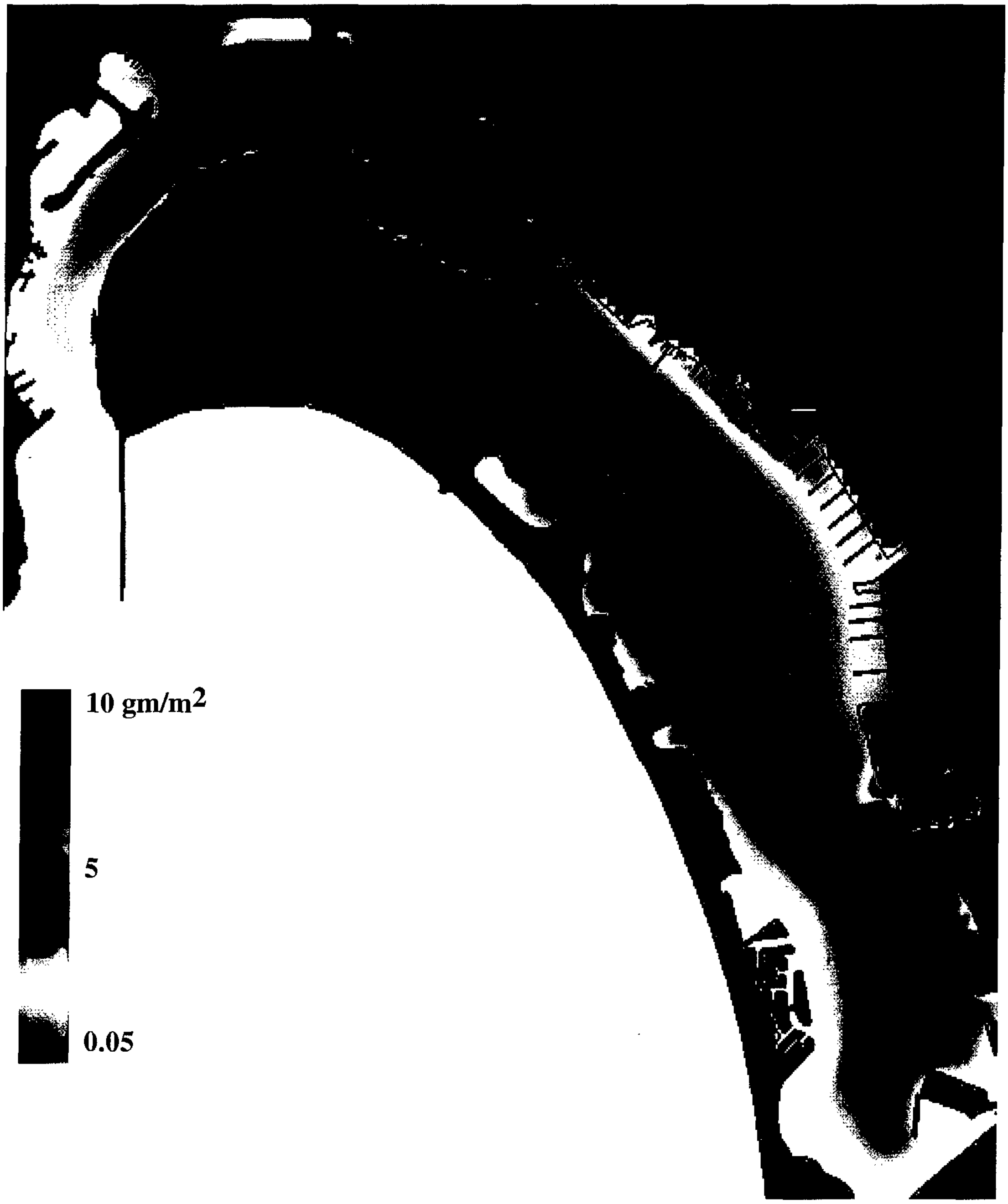

Figure 44. Bottom footprint of settled suspended solids less than 12 μm, which originated from Chollas and Paleta Creeks and Sweetwater River during an average storm event.

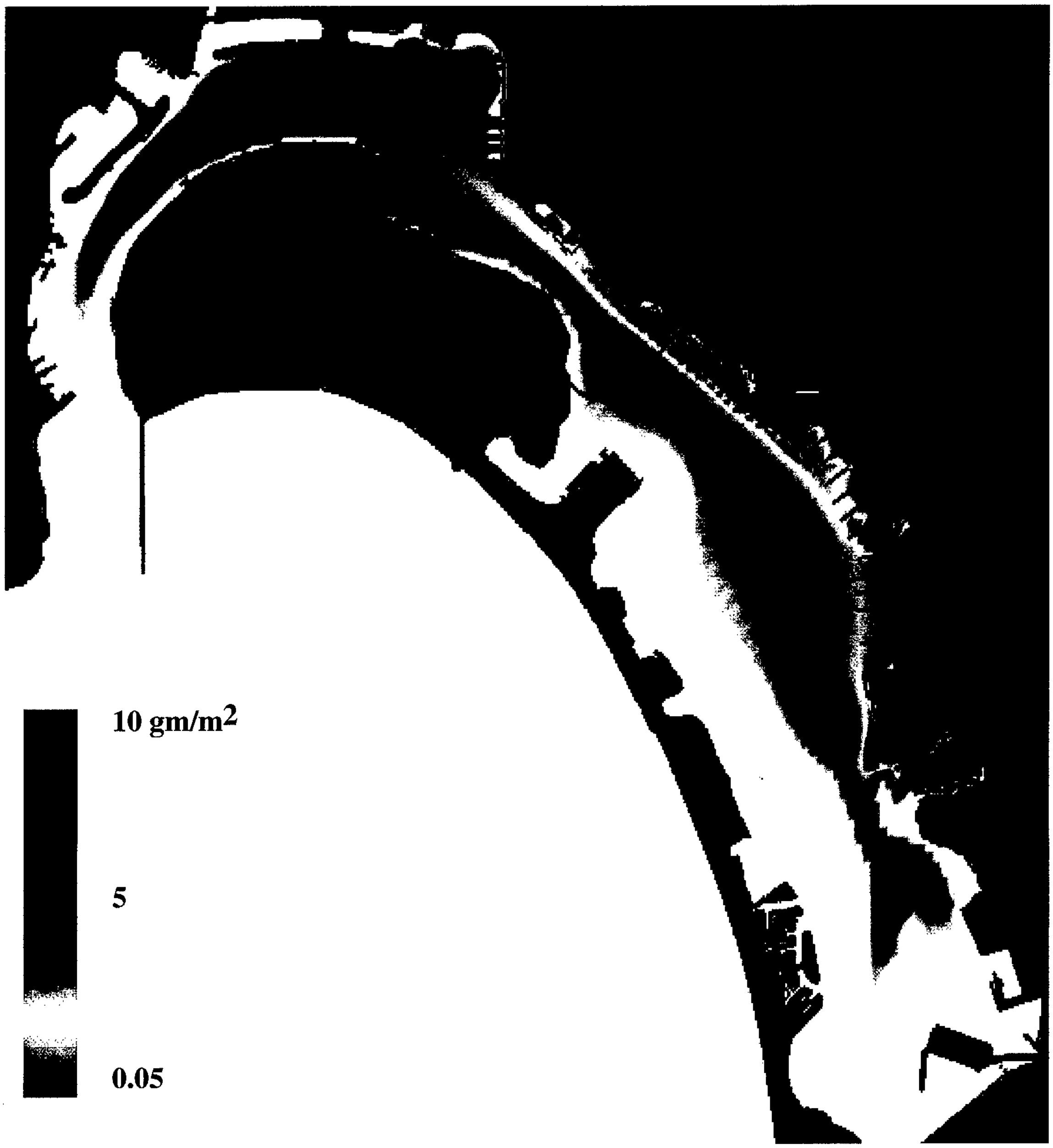

Figure 45. Bottom footprint of settled suspended solids between 12 to 55 µm, which originated from Chollas and Paleta Creeks and Sweetwater River during an average storm event.

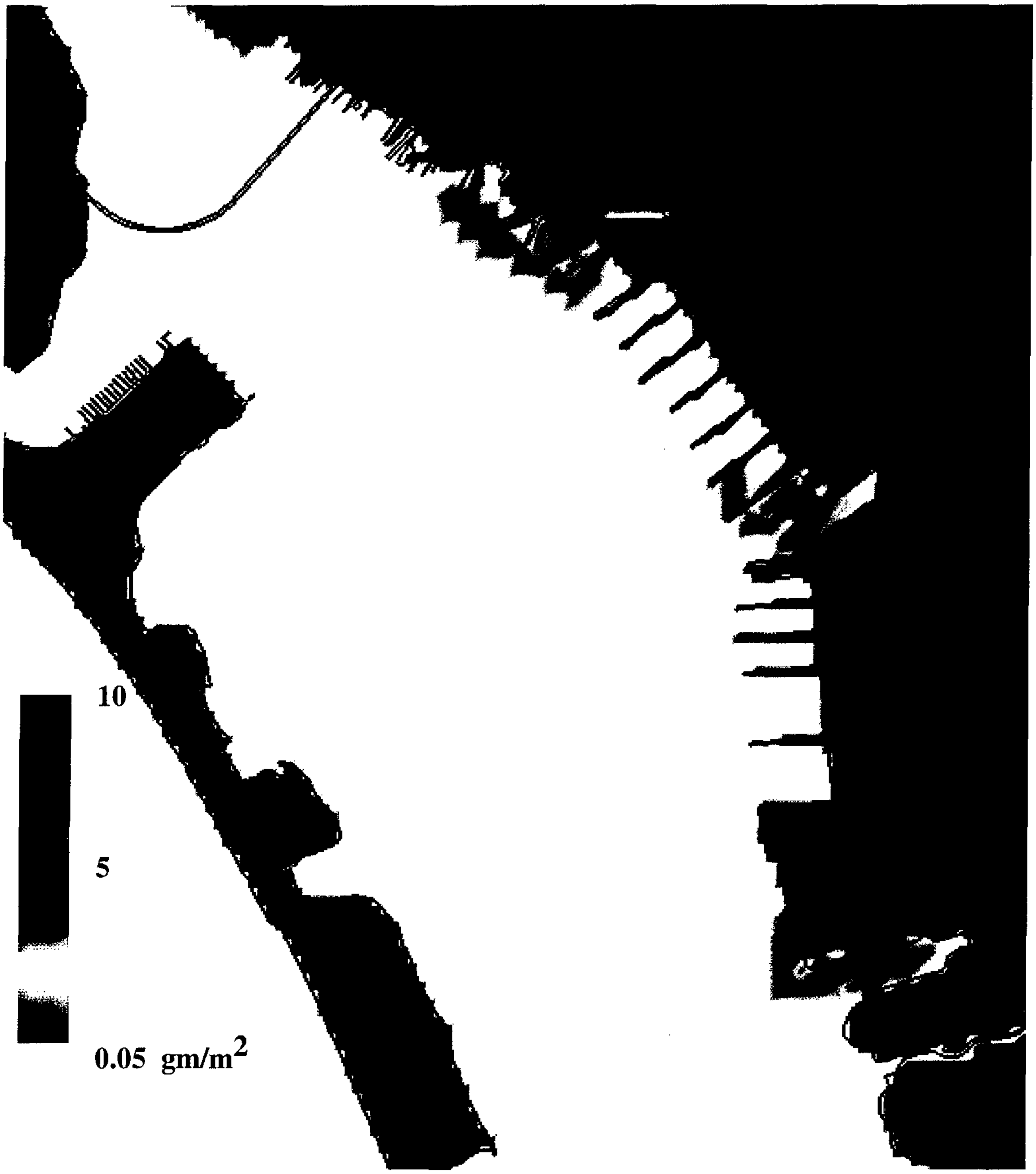

Figure 46. Bottom footprint of settled suspended solids between 55 to 250 μm, which originated from Chollas and Paleta Creeks and Sweetwater River during an average storm event.

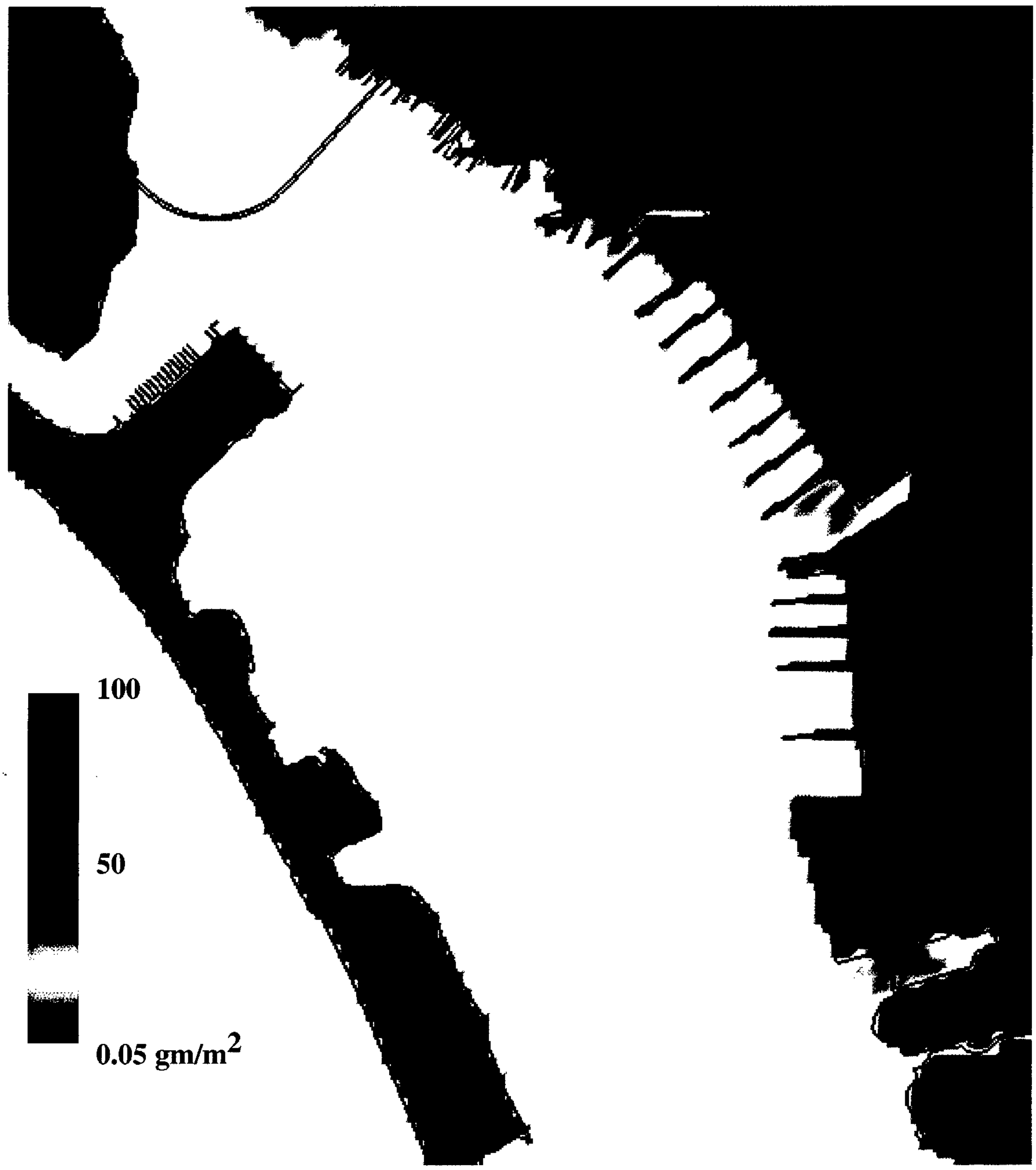

Figure 47. Bottom footprint of settled suspended solids greater than 250 μm, which originated from Chollas and Paleta Creeks and Sweetwater River during an average storm event.

Table 40. Loading and deposition of sediments from creek and river input to the NAVSTA region.

	Total Creek Loading		NAVSTA Bottom Settled			
	TSS	Cu	TSS	Cu	TSS	Cu
	$kg \cdot 10^3$	kg	$kg \cdot 10^3$	kg	percent	percent
Strong Storm	2737.1	252.6	978.0	66.5	35.7	26.3
Average Storm	487.2	29.5	63.5	7.9	13.0	26.8
Weak Storm	127.6	6.0	43.8	1.67	34.3	27.8
Yearly Basis						
All Strong	23539	2172	8411	572	35.7	26.3
All Average	7655	463	997	124	13.0	26.8
All Weak	4007	188	1375	52	34.3	27.8

6.4.3 Summary

A coupled, hydrodynamic/sediment transport model was applied to evaluate the transport and fate of sediments resuspended by ships and sediments introduced from creeks and rivers in the NAVSTA region. A survey of ship movements at NAVSTA indicates about 5 per day with 1 to 2 tugs per ship for a total of about 1730 ship movements per year. Field measurements indicate an overall resuspension rate of about 42,000 kg·day^{-1} (~15,000 mt·year^{-1}), representing about 29 percent of the background suspended load and about twice the estimated loading from stormwater inflow to the region (~7000 mt·year^{-1}). Some desorption was observed for metals during laboratory resuspension experiments. The experiments indicate that this desorption is unlikely to substantially increase water column concentrations for dissolved metals, although some increase in zinc loading on an annual basis could be expected. Remobilization for zinc during resuspension events was estimated at about 1400 kg·year^{-1}, similar to the input from benthic fluxes but smaller than inputs from creek sources. Input of cadmium from this source (~23 kg·year^{-1}), although much less than zinc, is significant compared to other known sources. Numerical modeling of transport of simulated ship resuspended sediments indicates that about 55 percent of the resuspended material could be deposited outside the pier area (~8250 mt·year^{-1}).

7. OVERALL CHARACTERIZATION

Conclusions and recommendations from this study focus on addressing the specific questions defined in the conceptual framework presented in Section 2. Our assessment of each of these issues is discussed below.

7.1 ARE CHEMICALS PRESENT AT ELEVATED LEVELS?

The most commonly accepted benchmark for evaluating sediment quality is the Effects Range-Median (ERM) level of Long and Morgan (1995). However, these thresholds are based on correlative analysis of chemical-toxicity relationships that do not necessarily imply a cause-effect relationship. Thus, the comparison of bulk chemical levels in the sediment to these thresholds should be viewed as only one possible indicator of sediment quality. Conclusions regarding chemical levels and their spatial distribution for this study were determined based on two criteria: (1) comparison to coastal background levels for "clean" sediments in regions that are thought to have limited anthropogenic impact, and (2) comparison to ERM. By using coastal background levels, the comparison with values from the bay will be on the high side because most operating harbors are impacted by anthropogenic activity that results in increased background in those areas.

7.1.1 Chemical Levels

Conclusions regarding chemicals that are present at elevated levels compared to effects thresholds (ERMs) and background levels can be summarized as follows:

- Concentrations of copper, mercury, and zinc were measured at elevated levels.
- Concentrations of silver, lead, PAHs, and PCBs were only occasionally measured at elevated levels.
- Concentrations of arsenic, chromium, and nickel were generally found to lie below ERM thresholds and at or near background levels.

7.1.2 Spatial Distribution of Chemicals of Concern

Chemicals identified above as having elevated levels in the overall NAVSTA region were evaluated further to determine in what specific areas they were found. In general, it was found that chemicals often tended to co-occur (e.g., copper and zinc), and were often associated with regions of high fines content such as clay or silt. Conclusions regarding the spatial distribution of these chemicals can be summarized as follows (refer to figure 26):

- The co-occurrence of elevated chemicals in regions of low benthic disturbance or stress and high fines content indicates that the accumulation of chemicals results from depositional and flushing processes, and not solely from proximity to sources.
- Of the areas within the NAVSTA piers, the highest incidence of chemical levels exceeding ERM thresholds was in Subregion 8, which lies along the quay wall between Piers 2 and 5.

- Within Subregion 8, silver, copper, mercury, zinc, PAHs, and PCBs were found at levels exceeding the ERM.

- Other areas within the piers that had some incidence of elevated chemical levels included Subregions 2, 9, 10, and 14. Subregion 2 is within the channel leading to Paleta Creek, Subregions 9 and 10 are adjacent to Subregion 8 in the area between Piers 2 and 7, and Subregion 14 falls along the quay wall in the area between the Mole Pier and Pier 13.

- Within Subregion 2, mercury, zinc, PAHs, and PCBs were found at elevated levels. In Subregion 9, copper, mercury, lead, zinc, PAHs, and PCBs were elevated, and in Subregion 10, copper, mercury, zinc, and PCBs.

- Areas within the piers that had a low incidence of elevated chemical levels included Subregions 1, 6, 7, 11, 12, 13, 15, 16, and 17. Subregions 1, 6, and 7 are located at the mouth of Chollas Creek, Subregions 11, 12, and 13 lie to the north of the Mole Pier, and Subregions 15 through 17 fall in the area between the Mole Pier and the 24th Street Marine Terminal.

- Within the combined area of Subregions 1, 6 and 7, the only elevated levels were for silver (1 site out of 31); copper (1 site out of 31); mercury (4 sites out of 40); and zinc (2 sites out of 31).

- Within the combined area of Subregions 11, 12, and 13, the only elevated levels were for copper (2 sites out of 20); mercury (4 sites out of 33); and PCBs (2 sites out of 17).

- Within the combined area of Subregions 15 and 17, the only elevated levels were for copper (3 sites out of 14—all near the PACO ore terminal) and mercury (9 sites out of 37).

7.1.3 Bioavailability of Chemicals of Concern

Bioavailability of chemicals was addressed by comparing pore water concentrations in sediments to published water quality criteria, comparing metals levels to sulfide binding capacity based on metal AVS/SEM ratios, and by direct measurement of bioaccumulation in mussels. Conclusions regarding bioaccumulation are included with bioassessment in section 7.2

- Low pore water concentrations for most metals and organics compared to water quality criteria indicate that chemicals within the sediment are not generally available at levels that are believed to cause effects. Some individual PAHs and total PCBs were found in the range of published chronic effect thresholds.

- Sediments in the NAVSTA region are typically rich in organic matter that leads to the presence of high sulfide levels and subsequent binding of metals in insoluble metal sulfides. In agreement with pore water chemistry, sulfide/metal ratios indicate that metals are not likely to be available at elevated levels within the sediment.

7.2 WERE EFFECTS OBSERVED IN BIOASSESSMENT STUDIES?

Biological effects from sediment exposure were evaluated based on numerous studies encompassing a broad range of test organisms and exposure mechanisms. Tests summarized below included bioassays, benthic community structure, in-situ biomarker assays, and bioaccumulation studies. In general, specific relationships between the physical/chemical characteristics of the sediment and biological effects were difficult to discern. One exception was the relationship between sediment contamination and Comet biomarker assay response that showed a clear correlation across the chemical gradient. Conclusions from the bioassessment studies can be summarized as follows.

7.2.1 Bioassay and Benthic Community Assessment

- In general, the spatial distribution of biological effects did not show clear patterns in relation to bulk chemical levels and physical property distributions.
- Regions with low incidence of chemical contamination displayed a broad range of biological effects incidence
- Regions with high incidence of chemical contamination generally showed a high incidence of biological effects
- Regions in which high incidence of contamination and biological effects co-occurred included NAVSTA Subregions 8 and 10 along the quay wall between Piers 2 and 7, and Subregions 4 and 5 within the commercial shipyards.

7.2.2 Biomarker Assessment

- Biomarker analysis of infaunal clams was not performed due to poor results for controls. Experiments were repeated using infaunal mussels. Infaunal mussel growth was impaired at NAVSTA stations, and biomarker response was elevated at stations NSB-1 and NSB-5.
- Biomarker analysis of water-column deployed (near bottom) and infaunal mussels showed a strong relationship with sediment chemical levels, particularly Cu and PAHs. The highest levels of response were found at Stations NSB-1 and NSB-3 (Pier 4) and NSB-5 (Inner Paleta Creek), in agreement with the co-occurrence of elevated chemicals. Low cell repair levels in *Mytilus* at Stations NSB-1 and NSB-3 suggest metals as the cause of measured effects at these stations.
- Moderate-to-high levels of response were observed in *Mytilus* at Stations NSB-4 (Pier 8), NSB-5 (Paleta Creek), and NSB-2 (Mid-Channel Reference Station). High cell repair levels suggest PAHs as the cause of measured effects at Station NSB-4.
- Stations NSB-2 and NSB-5 had moderate exposure to PAHs, but higher response levels at Station NSB-2. The shallow depth and high water clarity at that station suggest photoactivation as a controlling factor in PAH-induced effects.
- Lowest levels of response were observed at Station NSB-6 (West Reference Station).

7.3 ARE THERE ONGOING INPUTS FOR CHEMICALS OF CONCERN?

Ongoing sources of copper, zinc, lead, and PAHs were identified in the NAVSTA region. For other chemicals of concern, some sources were identified, but either could not be quantified, or appear too small to be significant. Known and potential source estimates that were derived as part of this study are summarized below.

7.3.1 Copper

- A large portion of the ongoing copper input to the NAVSTA region (total: ~4600 $kg \cdot year^{-1}$) comes from ship hulls while the remainder comes from stormwater runoff and pleasure boat hulls.
- The majority of the copper in stormwater comes from sources upstream of NAVSTA (~90%), with Chollas Creek as the largest single source. The percentage coming from upstream would probably be higher if event mean concentration (EMC) values were available for NAVSTA runoff sources, rather than only first flush data, because first flush data usually show the highest concentrations.

7.3.2 Zinc

- The majority of the ongoing zinc input to the NAVSTA region (total: ~15800 $kg \cdot year^{-1}$) comes from zinc anodes on ships (~66%) while the remainder comes from stormwater runoff and anodes on pleasure boats.
- The majority of zinc in stormwater comes from sources upstream of NAVSTA (~94%), with Chollas Creek as the largest single source. This percentage would probably be higher if EMC, rather than first flush, values were available for NAVSTA runoff sources.

7.3.3 Lead

- The majority of the ongoing lead input to the NAVSTA region (total: ~1130 $kg \cdot year^{-1}$) comes from stormwater.
- Most lead in stormwater comes from sources upstream of NAVSTA (~96%), with Chollas Creek as the largest single source. This percentage would probably be higher if EMC, rather than first flush, values were available for NAVSTA runoff sources.

7.3.4 PAHs

- Most recent PAH input to the NAVSTA region (total ~ 2980 $kg \cdot year^{-1}$) comes from creosote pier pilings (~87%) while the remainder comes from stormwater runoff, oil spills, compensating fuel-ballast systems, and atmospheric deposition.
- Inputs from bilgewater have recently been eliminated and ~50 percent of the pier pilings at NAVSTA have been replaced with plastic or untreated wood. Elimination of these two sources reduces loadings to the region by ~89 percent.

7.3.5 Mercury, Silver, and Cadmium

- Low-level inputs of mercury, silver, and cadmium have been identified in stormwater, however, known sources do not appear to account for measured levels in sediments. Sources of these chemicals may be historical.
- Mercury was used historically as an antifouling paint ingredient until about 1970 and appears to be present in the older berthing areas around the bay.
- Cadmium is contained in small amounts in zinc anodes although this appears to be a small source. Cadmium was also identified at terrestrial sites adjacent to the bay near the National City Marine Terminal.
- Possible historic inputs of silver include sewage discharges (CCREM, 1987) and industrial processes both on shore and aboard Navy ships. The extent of these sources is unknown.

7.3.6 PCBs

- Currently, there is insufficient data to quantify sources of PCBs. Historically, PCBs have been associated with industrial discharges and municipal waste discharges (MacDonald, 1996).

7.4 CAN SOURCES BE CONTROLLED?

Known sources of chemicals of concern were evaluated to determine the current and future potential for control efforts. It appears that some sources can or have been significantly curtailed, while others will likely continue until alternatives are developed.

- Input of copper from antifouling paints will probably continue for at least several years until alternatives are developed.
- Input of zinc from anodes will probably continue indefinitely although loadings may be reduced significantly by increased use of "impressed current" cathodic protection systems.
- Input of PAHs to the NAVSTA region should be significantly reduced in the next year.
- Input of chemicals from atmospheric deposition may decrease under stricter air quality standards.

7.5 DO IN-PLACE CHEMICALS REPRESENT A SIGNIFICANT RISK THROUGH REMOBILIZATION AND TRANSPORT?

Three mechanisms for remobilization and transport were investigated in this study including benthic fluxes, leaching from sediments resuspended by ships, and tidal transport of sediments resuspended by ships. These three mechanisms serve to re-introduce chemicals from the sediment to the water where they are potentially more bioavailable. They also serve to redistribute chemicals to other regions of the bay and potentially to assist in removal to the ocean. It appears that most chemicals of concern are not highly mobile and are unlikely to remobilize into the water even following resuspension events. Resuspension by

ships does appear to play a significant role in redistributing chemicals associated with sediment particles. Conclusions from these components of the study are summarized below.

7.5.1 Benthic Contaminant Fluxes

- Measurements were made for chemicals of concern including metals, PAHs, and PCBs. With the exception of zinc, fluxes of trace metals were generally low and not strongly correlated with bulk sediment concentrations, indicating that most metals are strongly bound within the sediment.
- Of the metals, sediment release was most common for zinc, with highest fluxes at Station NSB-3 (Pier 4) and Station NSB-5 (Paleta Creek). The estimated overall zinc flux from NAVSTA sediments was about 1400 $kg{\cdot}yr^{-1}$, about 10 percent of the overall zinc input to the region.
- Copper, lead, and cadmium showed limited release from the sediments at Paleta Creek, and copper also showed a positive release at Pier 4.
- Low release rates for copper were observed at other stations including Stations NSB-2, NSB-4, and NSB-6. Release rates for lead and cadmium were generally quite low.
- Limited data indicate no PCB fluxes and only limited release of PAHs from stations with elevated PAH bulk levels.

7.5.2 Resuspension by Ships

- A survey of ship movements at NAVSTA indicates just less than an average of five per day with one to two tugs per ship for a total of about 1730 ship movements per year.
- Field measurements indicate an overall resuspension rate of about 42,000 $kg{\cdot}day^{-1}$ (~15,000 $mt{\cdot}year^{-1}$), representing about 29 percent of the background suspended load and about twice the estimated loading from stormwater inflow to the region (~7000 $mt{\cdot}year^{-1}$).
- Some desorption was observed for metals during laboratory resuspension experiments. The experiments indicate that this desorption is unlikely to substantially increase water column concentrations for dissolved metals, although some increase in zinc loading on an annual basis could be expected. Remobilization for zinc during resuspension events was estimated at about 1400 $kg{\cdot}year^{-1}$, similar to the input from benthic fluxes. Input of cadmium from this source (~23 $kg{\cdot}year^{-1}$), although much less than zinc, is significant compared to other known sources.
- Numerical modeling of transport of simulated ship resuspended sediments were carried out for resuspension events within the NAVSTA pier area. Results indicate that about 55 percent of the resuspended material is deposited outside the pier area (~8250 $mt{\cdot}year^{-1}$).

- These modeling results suggest that a rough balance exists between sediments deposited in the pier area by storm events and sediments removed from the pier area by ship resuspension events.

8. ENDNOTES

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
January 1999

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
SEDIMENT QUALITY CHARACTERIZATION
NAVAL STATION SAN DIEGO: FINAL SUMMARY REPORT

5. FUNDING NUMBERS
PE: OMN
AN: DN307504
WU: D36–ME83

6. AUTHOR(S)
SSC San Diego
Computer Sciences Corporation
San Diego State University Foundation
County of San Diego
Arthur D. Little, Inc.
Water Resources Division, U.S. Geological Survey

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
SSC San Diego
San Diego, CA 92152–5001

8. PERFORMING ORGANIZATION REPORT NUMBER
TR 1777

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Commander, Navy Region Southwest
Deputy Assistant Chief of Staff, Environmental Department, Code N4512
33000 Nixie Way, Bldg 50, Suite 326
San Diego, CA 92147–5110

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The objective of this project was to provide an assessment of sediment quality in the area of Naval Station San Diego (NAVSTA). The study focused on two issues: the characterization of sediments including contaminant levels, extent and related ecological consequences, and the evaluation of processes that control the levels, transport, and biological exposure of any potential contaminants of concern. Sediments were characterized based on a range of physical, chemical, and toxicological testing. Processes evaluated included contaminant sources, sediment transport, sediment-water exchange, and degradation. As part of the object, new technologies for assessment and remediation were demonstrated and validated alongside traditional methods.

14. SUBJECT TERMS
Mission Area: Environmental Quality
ecology — environmental assessment
toxicology — biochemistry

15. NUMBER OF PAGES
162

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAME AS REPORT

21a. NAME OF RESPONSIBLE INDIVIDUAL	21b. TELEPHONE *(include Area Code)*	21c. OFFICE SYMBOL
S. Curtis	(619) 553-5255 e-mail: stacey@spawar.navy.mil	Code D362

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5 February 1999

Technical Report 1777
Sediment Quality Characterization Naval Station San Diego: Final Summary Report
By: B. Chadwick, et al.
Dated: January 1999

Literature Change

1. Please replace the cover, title page, Administrative Information page, and the Report Documentation Page with the attached corrected pages.

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1 April 1999

Technical Report 1777
Sediment Quality Characterization Naval Station San Diego: Final Summary Report
By: B. Chadwick, et al.
Dated: January 1999

Literature Change

1. Please replace page 77/78 with the attached corrected page.

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23 June 1999

Technical Report 1777
Sediment Quality Characterization Naval Station San Diego: Final Summary Report
By: B. Chadwick, et al.
Dated: January 1999

Literature Change

1. Please replace pages 41/42 and 109/110 with the attached corrected pages.

SPACE AND NAVAL WARFARE SYSTEMS CENTER SAN DIEGO
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25 August 1999

Technical Report 1777
Sediment Quality Characterization Naval Station San Diego: Final Summary Report
By: B. Chadwick, et al.
Dated: January 1999

Literature Change

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A359462 19991029000

SPACE AND NAVAL WARFARE SYSTEMS CENTER SAN DIEGO
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SAN DIEGO, CA 92152-5001

25 October1999

Technical Report 1777
Sediment Quality Characterization Naval Station San Diego: Final Summary Report
By: B. Chadwick, et al.
Dated: January 1999

Literature Change

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